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Agri-food policies and Sustainable Development Goals

Quantitative food system analyses

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Kurzfassung

Das Agrar- und Lebensmittelsystem ist der Schlüssel zur Erreichung mehrerer Ziele für nachhaltige Entwicklung (SDGs), insbesondere Ernährungssicherheit (SDG2), Abfallvermeidung (SDG12), Bekämpfung des Klimawandels (SDG13) und Schutz biologischer Vielfalt (SDG15). Die Europäische Union (EU) hat die SDGs oben auf ihre Agenda gesetzt. So wird der EU-Haushalt für die Gemeinsame Agrarpolitik (GAP) zunehmend an Nachhaltigkeitsziele geknüpft. Im global vernetzten Lebensmittelsystem können sich derartige politische Änderungen auf andere Regionen auswirken, etwa durch Handel, Preisweitergabe und Auswirkungs-Verlagerungen. Diese Dissertation beleuchtet potenzielle, auf Nachhaltigkeit ausgerichtete EU-Politikmaßnahmen, die auf verschiedene Akteure des Lebensmittelsystems abzielen. Kapitel 2 behandelt Konsumsteuern zur Erreichung von Ernährungsempfehlungen und ihre Auswirkungen auf Produktion, Umwelt und Lebensmittelkosten. Lebensmittelsteuern erweisen sich als wirksam um Ernährungs- und Umweltziele zu erreichen. Allerdings sind erhebliche Steuersätze erforderlich, um die angestrebten Ernährungsänderungen herbeizuführen. In Kapitel 3 werden Maßnahmen zur Reduzierung von Lebensmittelverschwendung mit solchen zur Verwertung von Lebensmittelabfällen als Schweinefutter kombiniert. Die modellierte Halbierung der Lebensmittelverschwendung führt zu größeren Emissionseinsparungen als ihre Verwertung als Schweinefutter. Marktwirkungen verringern die Einsparungen in der EU, aber ermöglichen zusätzliche im Ausland. Kapitel 4 widmet sich Auswirkungen umweltpolitisch motivierter Maßnahmen, die EU Agrarproduktion betreffend, auf den Handel mit afrikanischen Regionen südlich der Sahara (SSA). Die simulierte Beschränkung der Viehdichte und des Stickstoffeinsatzes verringert die EU Fleischproduktion. Dadurch sinken Umweltbelastungen und der EU-Anteil an Agrarhandelsströmen nach Afrika. Importe aus anderen Weltregionen und die steigende heimische Produktion füllen entstehende Versorgungslücken. Diese drei Studien verwenden ein agrarökonomisches partielles Gleichgewichtsmodell, welches mit Hilfe von Simulationen einen ganzheitlichen Blick auf Zielkonflikte im Lebensmittelsystem ermöglicht. Derartige Modellierungsinstrumente erlauben es jedoch nur in begrenztem Maße, Auswirkungen auf subnationaler Ebene zu untersuchen. Kapitel 5 ergänzt daher die bisherigen Studien um eine Entflechtung heterogener Ernährungsfolgen auf individueller Ebene. Mittels eines zweistufigen ökonometrischen Instrumentvariablen-Ansatzes werden die Auswirkungen unerwarteter Preisvolatilität auf die Ernährung von Kindern in SSA untersucht. Auch wird mit Ökonometrie/ Machine-Learning ermittelt, wie sich volatile internationale Termingeschäfte und Wetteränderungen auf die Volatilität lokaler Maispreise auswirken. Es konnte gezeigt werden, dass die Volatilität globaler Preise die lokale Preisvolatilität in SSA beeinflusst. Unerwartete Preisschwankungen verstärken Mangelernährung, insbesondere in ländlichen, landwirtschaftlichen und armen Haushalten. Diese Dissertation trägt zum Stand der Forschung bei, indem sie die Auswirkungen politischer Maßnahmen und Veränderungen im Lebensmittelsystem auf Ernährung, landwirtschaftliche Produktion und Umweltverschmutzungen untersucht. Die Ergebnisse betonen (i) die Unvermeidbarkeit von Zielkonflikten, (ii) die Relevanz von Heterogenität in den Folgen und (iii) die Auswirkungen der globalen Vernetzung durch Handel und Preisweitergabe und wie diese den Erfolg der Politik beeinflussen die notwendigen Verhaltensänderungen zu erzielen um die SDGs zu erreichen.

Abstract

The agricultural and food system is key to reaching several of the Sustainable Development Goals (SDGs), foremost those on food security (SDG2), reducing waste (SDG12), combatting climate change (SDG13), and reducing biodiversity loss (SDG15). The European Union (EU) has become a forerunner placing the SDGs on top of the political agenda. For example, the substantial EU budget under the Common Agricultural Policy (CAP) is increasingly subject to sustainability requirements. In a globally connected food system, such policy changes can cause spillover effects to other regions through trade, price transmission, and leakage.

This thesis sheds light on sustainability-motivated EU agri-food policy options targeting different actors within the food system. In Chapter 2, consumer taxes and subsidies designed to reach nutrition guidelines are assessed for their production implications, environmental benefits, and social burden. Food group specific taxes are found effective in reaching nutrition and environmental targets. However, considerable tax levels are required to achieve the targeted consumption shifts. Chapter 3 combines interventions for food waste reduction on the consumption side with those for food waste valorization as pig feed on the production side. Halving food waste generates larger EU emission savings than its valorization as pig feed. EU savings remain below those expected when not considering market feedbacks, but additional emission savings are projected to arise abroad as consequence of shifting trade flows. Chapter 4 presents the effects of environmentally-motivated EU agricultural producer policies on trade with sub-Saharan African (SSA) regions. Restricting livestock density and nitrogen application reduces EU production levels of meat. This lowers the EU's agricultural environmental burden and share in agricultural trade flows to Africa. However, imports from other world regions and increasing domestic production fill the supply gap. These three policy-focused studies are conducted using an ex-ante partial equilibrium agri-economic simulation model which allows for a holistic view on food system synergies and tradeoffs. However, the applied foresight modelling tools enable the investigation of food system implications at subnational level only to a limited degree.

Chapter 5 complements these studies by disentangling heterogenous nutrition outcomes at a more detailed level in an ex-post analysis. The effect of unexpected food price volatility on children's nutrition in SSA is assessed by using an econometric two-stage instrumental variable approach. In addition, the study investigates how international corn futures volatility and weather shocks affect local maize price volatility by applying econometrics and machine learning (i.e., gradient boosted trees, Shapley values) techniques. This analysis reveals that local price volatility in SSA is strongly driven by volatility in global futures prices. Unexpected nonseasonal price volatility increases the occurrence of stunting in children, particularly for rural, agricultural, and poor households.

This thesis contributes to scientific knowledge by disentangling the impacts of various agri-food policies and food system changes, in particular on food consumption, nutrition, agricultural production, and environmental pollution. The main findings highlight (i) the inevitability of tradeoffs, (ii) the relevance of heterogeneity in impacts, and (iii) the implications of global connectedness through trade and price transmission and how these affect policy success in stimulating behavioral change toward achieving the SDGs.

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Abbreviations

BMI	Body mass index
CAP	Common Agricultural Policy
CAPRI	Common Agricultural Policy Regionalized Impact modelling system
CGE	Computable general equilibrium
DHS	Demographic and Health Surveys
GLOBIOM	Global Biosphere Management Model
EU	European Union
FAO	Food and Agricultural Organization
GDP	Gross domestic product
GHG	Greenhouse gas
GHGE	Greenhouse gas emissions
HAZ	Height-for-age z-score
IPCC	Intergovernmental Panel on Climate Change
FWF	Food waste feed
MAGNET	Modular Applied GeNeral Equilibrium Tool
ML	Machine-learning
MUV	Mean unexpected volatility
N	Nitrogen
NRD	Nutrient rich diet score
PAL	Physical activity level
PE	Partial equilibrium
PMUV	Predicted mean unexpected volatility
ROW	Rest of the world
SDG	Sustainable Development Goal

SSA	sub-Saharan Africa
SSP	Shared Socioeconomic Pathways
UN	United Nations
WAZ	Weight-for-age z-score
WHO	World Health Organization
WHZ	Weight-for-height z-score

Chapter 1
Introduction

By adopting the Sustainable Development Goals (SDGs), the global community agreed to make the world more environmentally friendly, increase social justice, and fight malnutrition. The agricultural and food sector is key to reaching several of the SDGs, foremost those on food security (SDG2), reducing waste (SDG12), combatting climate change (SDG13), and reducing biodiversity loss (SDG15). Agricultural policies are increasingly designed toward these goals. Nonetheless, policies' impacts on the food system and on metrics relevant to SDGs remain unclear.

While pursuing SDGs is a joint global commitment, the implementation of necessary policies to reach these aims can hardly be enforced on international level due to missing jurisdictional possibilities to ensure enforcement. Therefore, the action of single countries or political unions can be a role model and stimulate action in further regions. The European Union (EU) has taken various steps to take on such a role, for example when setting the "Green Deal" as the new overarching policy framework. Within this framework, the substantial EU budget for the agri-food sector under the Common Agricultural Policy (CAP) will increasingly be subject to sustainability requirements. Traditionally, the CAP has been production-side focused. However, some policy objectives might more efficiently be addressed by consumer-side policies or by a combination of both within a comprehensive policy package. Policies designed to improve sustainability with a specific focus may (unintendedly) affect other aspects of sustainability as well. A recent example for tensions between sustainability dimensions, i.e., food security vs. environmental protection, is the discussion around pausing environmental obligations for EU agricultural production to support the supply of global cereals given production shortfalls related to the war in Ukraine (European Commission, 2022). To assess the overall success of a policy considering its synergies and tradeoffs with other policy objectives, thus a food system perspective needs to be taken.

This thesis sheds light on sustainability-motivated EU agri-food policy options targeting different actors within the food system. In Chapter 2, consumer taxes and subsidies designed to reach nutrition guidelines are assessed regarding their production implications, environmental benefits, and social burden. Chapter 3 combines interventions for food waste reduction on the consumption side with those for food waste valorization as pig feed on the production side. While both these chapters also evaluate underlying trade implications, this aspect gets a distinct focus in Chapter 4. Here, we[1] analyze the effects of environmentally-motivated EU agricultural producer policies on trade with, as well as production and consumption implications in Sub-Saharan African regions.

These three policy-focused studies are conducted using an ex-ante partial equilibrium agri-economic simulation model which allows for a holistic view on food system synergies and tradeoffs. Moreover, potential policy implications can be assessed before their actual implementation. Apart from main policy effects, our model results also indicate the heterogeneity of their implications, e.g., for different income groups or for net consuming vs. net producing households. However, given the level of aggregation, conclusions regarding individuals' socio-economic, nutrition, or health consequences remain coarse and assumptive when applying such a simulation modelling approach.

[1] The performed research in this thesis is described with reference to the first person plural. Despite that the presented work was mainly conducted by myself, many coauthors contributed to this work and improved the analyses with their admirable expertise. In the beginning of each chapter, credit author statements are included to ensure transparency and give credit to each contribution.

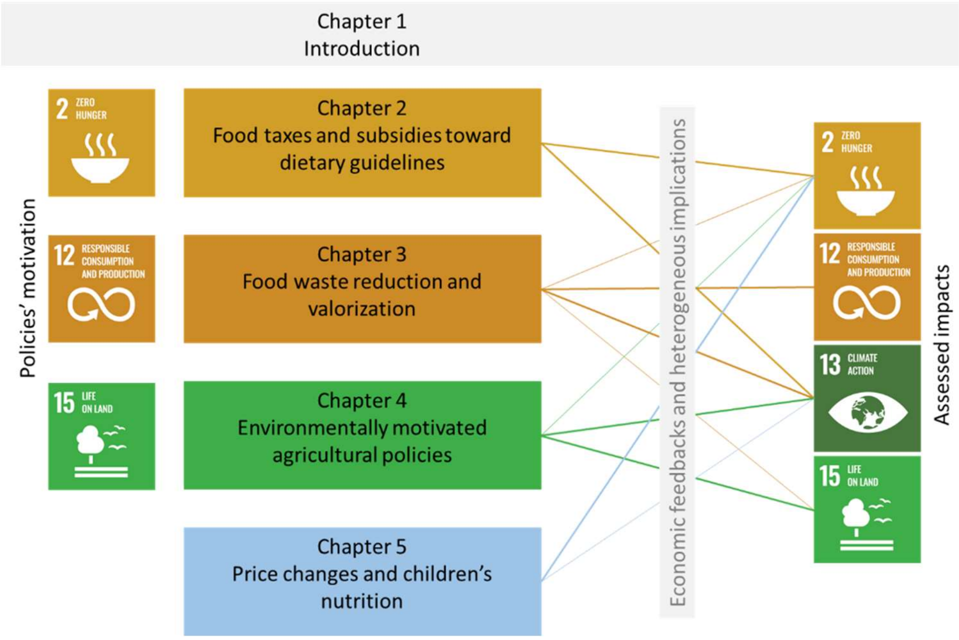

Figure 1.1 Structure of the thesis and links of chapters to SDGs

Note: Thicker lines indicate the impacts we focus on, thinner lines indicate that SDG impacts are somewhat related but either effects are small or not assessed. Chapter 5 does not present a policy analysis

Chapter 5 complements the previous chapters by disentangling heterogenous nutrition outcomes at a more detailed level. Using a combined econometric and machine learning approach, we assess economic, socioeconomic and environmental drivers for nutrition outcomes among children in sub-Saharan Africa. Our focus is to disentangle how food price volatility affects different nutrition measures. We use an instrumental variable approach and find that especially stunting increases as a consequence of high unexpected price volatility, most strongly for children in rural, poor, and agricultural households. Moreover, in a decomposition analysis we show that local unexpected maize price volatility is considerably driven by international corn futures movements.

This thesis contributes to scientific knowledge by disentangling the impacts of various agri-food policies and food system changes, in particular on food consumption, nutrition, agricultural production, and environmental pollution relevant for several SDGs (Figure 1.1). The main findings highlight (i) the inevitability of tradeoffs, (ii) the relevance of heterogeneity in impacts, and (iii) the implications of global connectedness through trade and price transmission and how these affect policy success in stimulating behavioral change toward envisaged policy goals.

The remainder of this chapter is structured as follows. Section 1.1 provides an overview of the reasoning and design of the sustainability-motivated policies assessed in this thesis. In Section 1.2, the interrelations of global agri-food system changes and its implications at local level are discussed. In Section 1.3, the quantitative methods used in the presented analyses are introduced. Section 1.4 summarizes the findings with respect to consequences for SDG indicators, the role of economic feedbacks, and the relevance of considering heterogeneity underlying those effects. Section 1.5 concludes this chapter with take-aways regarding synergies and tradeoffs in achieving SDGs and the implications for policy-making derived from our findings.

1.1 **EU agri-food policies for SDGs**

With the "Green Deal", the EU set the motivation to become more sustainable in various policy domains. Especially the agri-food sector is subject to many sustainability concerns. For example, food production is related to environmental impacts in form of greenhouse gas emissions (GHGE) and nitrate pollution, and food consumption affects nutrition and food security. Thus, policy-making has great potential to improve the sustainability performance of the agri-food system.

To steer consumer and producer behavior toward the SDG targets, policy-makers can choose from a repertoire of different policy instruments. Their effectiveness and appropriateness are context-dependent. Table 2.1 in Chapter 2 summarizes policy instruments, their restrictiveness in terms of freedom of choice, and their effectiveness in steering food consumption changes according to preceding research. In Chapters 2 – 4 of this thesis, policy instruments, that are designed to contribute to different SDGs and are implemented at either the consumption- or production-side, are analyzed in terms of their implications related to synergies and tradeoffs between sustainability dimensions. The investigated policies in these chapters and the motivation underlying their design are described in the following.

1.1.1 *EU food taxes and subsidies for SDG2*

Monetary policy instruments are discussed to be efficient measures to internalize external costs by making the prices consumers or producers are facing an approximation of the “true cost” of a product (Lusk, 2013). External costs are related to both, environmental and health impacts, resulting from unsustainable or unbalanced diets (Willett et al., 2019). Chapter 2 describes a joint modeling effort to identify consumer tax and subsidy levels necessary to steer EU average food consumption to comply with dietary guidelines. Based on scientific evidence (Mertens et al., 2018), the consumption shift needed on EU average to comply with dietary guidelines is approximated. By 2050, dietary changes for three product groups, i.e., sugar, meat, and fruits and vegetables, are achieved in three ex-ante simulation models via price adjustments. The resulting price changes are interpreted as necessary tax and subsidy levels to align EU consumption with dietary guidelines and to reach nutrition security as part of the ambitions under SDG2 on EU average. The model results suggest large tax rate increases to reach substantial dietary change. The regressive nature of such taxes (Nnoaham et al., 2009) makes these a highly debated and politically rather unpopular instrument. Therefore, explicit taxes for steering food consumption have been implemented in real life context only as an exception (Colchero et al., 2016; Smed, 2012) (besides taxes on alcohol). However, currently a reduction of the value-added tax on fruits and vegetables is discussed, e.g., in Germany, as an instrument to ensure food access for low-income consumers in times of increasing food prices, that are also a consequence of the war in Ukraine in 2022, and to simultaneously incentivize healthier food choices (Bentley, 2022; Osendarp et al., 2022).

1.1.2 *EU food waste reduction and valorization for SDG12*

Information campaigns are regarded as promising and least intrusive instruments to steer human behavior (Table 2.1 in Chapter 2). However, measuring their effectiveness and the durability of achieved behavioral changes proves difficult in real-life settings (Hyseni et al., 2017). Ex-ante modelling usually employs preference shifts to simulate the successful implementation of an information campaign, hardly being able to fully capture the occurring costs of the campaign and the desired changes. By using preference shifts, we do not assess how a campaign should be designed to be successful. However, we can analyze the implications of the desired changes under the assumption that the information campaign has led to the intended behavioral shift.

In Chapter 3, we assess the implications of a successful information campaign to reduce avoidable food waste at household level by 50%. This scenario is also analyzed in combination with a valorization attempt for plant-based food waste to be used as a component in pig feed. As part of a sensitivity analysis, the producers' costs for the "circular" novel feed component are varied to investigate if using food waste as input to pig production would be an economically rational decision. Both policies, the information campaign on the consumption side as well as an enforced valorization system at the production side, could contribute to reducing food waste and thus to reaching SDG12, that targets the reduction of waste.

1.1.3 *Environmentally motivated CAP changes for SDG15*

Restrictions and bans are the most restrictive policy instruments discussed in this thesis in terms of limiting the freedom of choice of the actors, whose behavior they affect (Table2.1 in Chapter 2). Such intrusive interventions can be especially welfare reducing as the market mechanism is not used to "organize" behavioral change at the lowest welfare cost. Yet, restrictions can be regarded an appropriate measure in cases where a market-based instrument is difficult and costly to implement and the current status is causing considerable but preventable harm. In Chapter 4 we investigate two kinds of environmentally motivated instruments to steer agricultural production in the EU, restrictions and subsidies. The restrictions refer to nitrogen surpluses and livestock density per hectare. They are analyzed in addition to a change of the CAP payment structure. This subsidy change is composed of a reduction of CAP Pillar I payments, focused on income support, and a transfer of the saved budget to Pillar II payments subsidizing extensive crop production practices.

Both policy interventions are motivated by the intention to make EU agricultural production more environmentally friendly. They relate to targets under SDG15[2] by the presumable advantages of extensive production and reduced nitrogen surpluses for ecosystems and biodiversity in agricultural landscapes.

1.2 Global agri-food system – local consequences for SDG2

In the globally interconnected food system of the 21st century, policy and market changes in one region can cause spillover effects to other regions. First, trade flows and globalized value chains affect market quantities and prices beyond the boundaries of the region in which the effect originates. Second, the actual policy impact within the implementing region is subject to trade that may weaken the intended effect if not taken care of in the policy design. Third, leakage effects may cause an unintended displacement of policy impacts (Lima et al., 2019). Lastly, policies can also spill over to other regions if they are regarded successful and inspire policy-making abroad. And, with trade policies and standards, regions can also influence production patterns in trading-partner regions.

Changes in the global agri-food system can trickle down to the local level. Alterations in global trade flows and large-scale production and consumption shifts, may finally influence production and consumption decisions of local actors around the world. How strongly local (small-scale) actors are affected depends on their involvement in global value chains subject to local market integration and access (Abbott and Borot de Battisti, 2011; Cudjoe et al., 2010). Fear of increasing malnutrition in low- and middle- income countries caused by rising food prices as consequence of supply shortages due to the Ukraine war in 2022 are a current example that

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[2] By their targets, the SDGs are as well linked to each other, despite their "focus" topic, that we mainly refer to in this overview. For example, SDG2 Target 2.4, *ensuring sustainable food production*, addresses the link between agricultural production and ecosystem maintenance.

reveals the level of globalization in the food system (Bentley, 2022; Osendarp et al., 2022).

Furthermore, the food system is facing global threats such as climate change. The agricultural system itself contributes to a quarter of global greenhouse gas emissions (Tubiello et al., 2015). Agri-food value chains are, and will increasingly be, affected by climate change, for example in terms of rising temperature levels and more frequent extreme weather events such as droughts and floods (Calzadilla et al., 2013). The implications for local food system actors vary by their characteristics. Wilts et al. (2021)[3] investigate climate-change induced yield shifts and their implications for different household types in selected low-income countries. The study emphasizes that impacts on market prices and quantities affect households differently depending on their degree of wealth, ruralness, and involvement in the agricultural sector. However, an analysis of implications at household-member level and for detailed food security indicators remains beyond model boundaries and scope of the study.

In Chapter 2 – 4, we face similar limitations caused by a high level of aggregation across population subgroups. While our modelling analyses are somewhat detailed in projecting subnational implications for EU agricultural production, consumption, and trade effects to non-EU regions are discussed at national level only. We project changes in trade-flow, production, and consumption patterns at national level that result from EU policy changes. For example, in Chapter 4, we focus on changes in agricultural trade flows to Africa as consequence of more environmentally friendly EU agricultural policies. We explore trade flow adjustments between African and other regions and compare effects of producer and consumer prices to deduce implications for net agricultural producers and net food consumers in sub-Saharan African regions.

Our findings of these policy assessments contain valuable insights for policy-makers to increase awareness of tradeoffs and synergies related to their decisions. However, at subnational level, we can only provide reasonable, literature-informed interpretations regarding the implications of

[3] I contributed to this article during the time of my doctoral studies. It is not part of this thesis as a main chapter.

national level impacts, e.g., assessing that low income households react more elastically to price changes (Cudjoe et al., 2010), but we cannot disentangle the actual effect at household level as such using this foresight modelling approach.

In Chapter 5, we apply an econometric approach to disentangle food security implications resulting from price changes at a more detailed level, i.e., for individual children. We investigate the effect of local price changes on children's nutrition in sub-Saharan African countries. To capture the influence of the global agri-food system at local level, we assess in how far volatility in corn futures affects local market price volatility for maize using econometrics and machine learning. In addition, we control for regional weather shocks and discuss their contribution to price movements and nutrition outcomes. With this approach we shed light on the role of staple food prices for reaching targets under SDG2, such as *ending all forms of malnutrition*.

1.3 Quantitative methods

1.3.1 *Ex-ante simulation modelling and model assumptions*

In all three ex-ante policy analyses (Chapter 2 – 4) we apply the Common Agricultural Policy Regionalized Impact (CAPRI) modelling system. This is a comparative-static, partial equilibrium agricultural sector model developed for policy and market impact assessments from global to regional and farm-type scale. The modelling system contains a spatial, non-stochastic global multi-commodity model. It is defined by a system of behavioral equations differentiated by commodity and geographical units. Food consumption at country level is calibrated using FAO food balance sheets and Eurostat (Britz and Witzke, 2014). Consumer demand is based on generalized Leontief expenditure functions (Ryan and Wales, 1999). Resulting indirect utility functions depend on prices and increase in income. CAPRI uses the 'Armington (1969) approach' to represent international trade and to differentiate imported from domestic products and by country of origin.

In addition, two further ex-ante simulation models are applied in the analysis presented in Chapter 2: The Global Biosphere Management Model (GLOBIOM) and the Modular Applied GeNeral Equilibrium Tool (MAGNET). GLOBIOM is a partial equilibrium model that covers global agricultural, bioenergy, and forestry sectors (Havlík et al., 2014; Frank et al., 2015), whereas MAGNET is a multi-regional, multi-sectoral, general equilibrium model based on neo-classical microeconomic theory (van Meijl et al., 2006; Woltjer and Kuiper, 2014). The multi-modelling approach applied in Chapter 2 increases the reliability of direction and magnitude of the findings.

Scenario implementation differs by the chosen policy instruments in each chapter. To quantify the necessary price changes for reaching the nutritionally recommended dietary changes, we focus on tax and subsidy instruments in Chapter 2. We impose recommended consumption changes for different food groups and total calorie intake and leave the respective prices to be changed endogenously by the models. We interpret the resulting price changes as consumer taxes. In contrast, in Chapter 3, the consumer food waste reduction scenario is implemented as a preference shift cutting the baseline avoidable food waste by 50%. We interpret this as the result of a successful food waste information campaign. The food waste valorization as pig feed is, due to data limitations, modelled by adjusting pig nutrient requirements to represent only the remaining nutrients supplied by conventional feed. Thus, nutrients from food waste become an enforced component of the pigs' diets. In Chapter 4, increased environmental subsidies are implemented as a transfer of the budget freed-up by cutting the payments related to CAP Pillar I in half to subsidies with a focus on extensive crop production under Pillar II. Restrictions to reduce nitrogen surplus are implemented as maximum animal density subject to the respective local soil nitrogen needs in the baseline scenario. In addition, we impose soil nitrogen surplus limits of 50 kg N per hectare and year. Both restrictions are assessed individually and in combination.

1.3.2 *Ex-post econometrics and machine learning*

In Chapter 5, an ex-post assessment combines econometric and machine-learning tools. The chapter is based on two related components. First, a decomposition of unexpected local maize price volatility is performed. We focus on unexpected nonseasonal volatility as this is supposed to be most difficult for households to anticipate and thus potentially most harmful to food security (Amolegbe et al., 2021). In addition to a fixed effects linear regression model, we apply a machine-learning approach using gradient boosted trees that does not pre-impose restrictions related to the functional form. In addition, we perform a Shapley value decomposition to understand the relation between the explanatory variables ("features") and unexpected price volatility.

Second, we analyze the effects of unexpected local maize price volatility on children's nutrition using linear fixed effects regression models of different specifications. Overall, we compare six nutrition indicators in a multi-regression analysis. In order to avoid endogeneity problems (i.e., simultaneity, omitted variable bias) between the price volatility indicator and the nutrition variables, we use a two-stage instrumental variable approach taking the predicted values from the fixed effects price volatility decomposition as main explanatory variable of interest in the second stage. In addition, we compare modified price volatility indicators for a robustness check on the findings.

Overall, in this thesis, different methodological approaches are used. These include (i) ex-ante foresight simulation modelling based on a partial agricultural economic equilibrium model, (ii) ex-post econometrics pursuing an instrumental variable approach moving toward the identification of causal impacts, and (iii) machine learning tools including gradient boosted trees and Shapley value decomposition. These quantitative methods are based on thorough literature review sections as part of the different chapters.

1.4 SDG impacts, economic feedbacks, and heterogeneity

1.4.1 *Main impacts on SDGs in focus*

In Chapter 2, diet taxes and subsidies are motivated by dietary improvements to address nutrition security in line with SDG2. All three simulation models support the conclusion that the EU will miss the diet recommendations on average in 2050 without interventions.

The envisaged diet change is exogenously enforced in the simulations and thus nutrition improves on EU average by scenario design. Our model results show that such a considerable diet shift would require high tax levels. Enforcing the shifts towards recommended diet patterns increases food expenditures. However, as household income is projected to rise much stronger over time until 2050, the share of household budget needed for food remains moderate.

Scenarios in Chapter 3 are motivated by SDG12 that targets waste reduction. Avoidable consumer food waste rates are reduced for EU consumers by a preference shift implemented for purchases of previously wasted food. Endogenously changing prices counteract the resulting purchase decline slightly. In an alternative scenario, all available plant-based consumer food waste in a country is assumed to be available for pig feed. The resulting "food waste feed" is a rather low-protein, high-energy feed alternative. Its provision at low cost could be regarded as an implicit subsidy to pig production and results in falling EU producer prices for pork meat and cereals. Due to its low protein content, food waste feed is only a competitive alternative at a price of maximum 50% of the price for conventional pig feed.

Scenarios in Chapter 4 are motivated with reaching improvements related to SDG15. When restrictions are imposed, nitrogen surplus is reduced as enforced. In comparison, shifting subsidies to the favor of extensive crop production shows minor improvements regarding environmental pollution. The payment transfer shifts production slightly toward more extensive, but also less profitable production activities.

Enforcing stronger regulations for nitrogen application and animal density restrictions implies small changes in crop and dairy production, whereas meat production decreases more strongly. By scenario design, EU average herd sizes decline. As a result, in those regions with the highest nutrient surpluses in the reference situation, a decrease of up to 88% is found.

In Chapter 5, we assess the impact of unexpected local market price changes on nutrition indicators for children in sub-Saharan Africa. Our nutrition price analysis suggests that unexpected nonseasonal price volatility increases the occurrence of stunting in children. The impacts are especially large for rural, agricultural, and poor households. However, we do not find similarly robust effects for all other nutrition indicators.

1.4.2 *Food system feedbacks and SDG13*

Policies that are designed toward a certain sustainability goal will hardly leave the rest of the food system unaffected. Through market feedbacks, producers are affected once a policy influences consumer behavior, and vice versa. These feedbacks spread through the global food system via complex trade-flows.

In Chapter 5, one of our objectives is to understand the extent of price transmission to local market price movements. We find that local price volatility is considerably driven by futures volatility. Price implications from policies or other food system shocks that happen anywhere can thus easily be channeled to local markets in very different places.

Since the production side is contributing most to agricultural greenhouse gas emissions along the food chain (Garnett, 2011), trade impacts determine by how much and where these are affected as a result of a policy intervention. We assess market and trade feedbacks of the food system and agricultural greenhouse gas emissions for all three ex-ante studies that are presented in detail in Chapter 2 – 4. These effects are summarized briefly in the following.

In Chapter 2 the locations where emission savings result as consequence of EU food taxes vary due to different trade responsiveness between models. GLOBIOM and MAGNET results show a decline in EU agricultural non-CO_2 GHGE emissions, whereas the reductions appear to be comparatively small in the CAPRI results. However, strong emission reductions are suggested by CAPRI as well, though mostly in non-EU regions. In any case, strong demand reductions for sugar, and red and processed meat decrease production of these products – either in the EU or in trading-partner countries.

In Chapter 3, we find that food waste reduction causes production changes that can indirectly affect food intake in and outside the EU. Cutting avoidable consumer food waste by 50% in the EU results in a much stronger shock than valorizing plant-based food waste as pig feed. Food intake and food system changes are therefore considerably stronger in the former scenario. Still, food waste valorization non-negligibly affects pig- and pig feed-producing sectors.

Trade reactions impact food production and prices outside the EU in all food waste scenarios. In the case of food waste valorization, pork production in African countries declines most dominantly. Cereal producers outside the EU are negatively affected, but the EU increases oilcake imports to supply increased protein feed demand to balance high-energy food waste feed.

In total, agricultural emission savings from food waste valorization are much lower than those related to the reduction of avoidable food waste. Trade changes prevent EU agricultural production from declining as much as EU food demand and additional emission savings occur abroad due to demand-side policies succeeding to reduce avoidable consumer food waste. At the global level, our assessment shows that these might achieve an over-proportional reduction of GHGE due to considered regional differences in emission-intensities of agricultural production.

Chapter 4 is focused on the effects of environmentally-motivated agricultural EU policies on trade with Africa and the implications for the African agricultural sector. In comparison, food system impacts from a shift of subsidy payments toward supporting extensive production are minor.

When enforcing stronger regulations for nitrogen application and animal density, CAPRI suggests that EU consumer prices for meat increase and meat intake is reduced on EU average. Domestically, the EU fills part of the gap in domestic supply by increased imports and reduced exports to other countries. African imports of meat and dairy products from the EU show a substantial decline, whereas imports of cereals and oilcakes from the EU increase as consequence of the drop in EU feed demand. Reduced African meat and dairy imports from the EU are mainly compensated by increasing imports from other world regions. A smaller share is offset by additional African production. EU agricultural greenhouse gas emissions decrease by up to 8%. Part of the production decrease in the EU is compensated by increased production in other countries, which goes along with emission leakage weakening the actual reduction achievement for the global emission burden.

In Chapter 5, food system feedbacks are underlying drivers of local price changes and also influence nutrition outcomes. Controlling for mean temperature and total rainfall proves to be important for assessing the impact of price volatility on children's nutrition. The differentiation between direct impacts on nutrition (e.g., through weather shocks such as heat extremes or diseases on health) and indirect impacts that are channeled through price volatility require further exploration. Such weather shocks are expected to become more frequent with accelerating climate change (Ebi et al., 2021).

1.4.3 *Heterogeneous impacts and SDG2*

One main takeaway from all analyses of this thesis is that implications from food system shocks can be heterogeneous across actors. For example, agri-food policies will cause different consequences for producers vs. consumers, for rich vs. poor households, for domestic actors vs. those in trading-partner countries.

In our simulation model analyses in Chapter 2 – 4, we disentangle these effects to the extent possible given the level of aggregation in the model. In Chapter 5, we make use of a much higher level of detail in our data to compare household types.

Chapter 2 suggests that high price changes are necessary to steer a population-wide diet shift. This raises concerns regarding distributional effects and food affordability for low-income households. Food consumption in CAPRI is however based on a single representative consumer per country. Additional assessments based on micro-level data could thus help addressing such distributional questions, also under consideration of potential differences in exposure to diet-related health risks. Moreover, a redistribution of tax revenues could help to reduce social equity concerns when actually implementing tax measures.

In Chapter 3, we find that EU food waste reduction and valorization lead to lower food prices across some product groups which facilitates food access for net consumers, also in low-income trading-partner countries. However, for consumers who already exceed recommended intake levels of some foods this can have undesirable impacts on nutrition. The reduced food demand related to a reduction in EU consumer food waste negatively affects the income of producers in the EU — and via trade effects also elsewhere.

In Chapter 4, we discuss implications of price changes in Africa resulting from more environmentally friendly agricultural policies in the EU. Nitrogen surplus restrictions for EU agricultural producers cause cereal exports to and meat imports from other countries. In consequence, the situation for African cereal producers deteriorates slightly whereas income of pork producers likely increases due to rising producer prices. For African consumers, increased pork prices lead to a reduction of pork consumption by 4%. For consumers already struggling to access a diverse diet, small price increases could threaten their food security.

Distributional consequences that could follow from such a policy shift for EU farmers are not discussed in depth. Still, for farmers reliant on CAP Pillar I subsidies or on a certain production quantity to cover their costs, resulting production declines could imply their dropping-out of the market and a further concentration in the sector. Whether any production reduction would materialize as a small decline by many farmers or by a complete dropout by few is not distinguished by the model.

In Chapter 5, heterogeneity of food system impacts can be analyzed at a much more detailed level. We find that higher mean unexpected volatility significantly increases stunting in children across household groups. The effects are particularly large for rural, agricultural and poor households. In general, boys are more exposed to stunting than girls, although, the effect is rather small. Being a twin is also related to stunting, especially in rural, less wealthy, or farming households. Furthermore, limited parental education increases the occurrence of stunting across various subgroups. Unexpected volatility reduces diet diversity, most strongly for younger children under the age of two years. Generally, being urban, rich, and older is related to higher diet diversity.

1.4.4 *Limitations*

All the analyses presented in this thesis are subject to limitations. These relate to model boundaries, underlying theoretical assumptions, or variable specifications. Not all limitations can be easily addressed, but some hold the potential to be addressed by future research.

In Chapter 2, the models suggest high tax levels to achieve the substantial, envisaged changes in food consumption to be in line with dietary recommendations on average. Such a considerable behavioral change compared to the baseline may push the applied models beyond the range of validity of their implemented consumer price responsiveness. The large-scale diet shift, however, deviates strongly from the model calibration points and likely implies too rigid model behavior. Therefore, the resulting tax levels should be interpreted with caution, focusing rather on the order of magnitude than on the exact values.

In Chapter 3, not all environmental impacts from land-use change have fully been accounted for e.g., those related to deforestation. Thus, emission savings from the valorization as animal feed could be smaller due to unaccounted impacts from additional soya imports, whereas those related to halving avoidable consumer food waste might be underestimated by savings in unaccounted emissions. By applying a partial equilibrium model, we do not fully account for rebound effects. Food waste treatment, handling, and collection are beyond the model's system boundaries. Also, we do not consider compliance, opportunity, or policy implementation costs and we do not account for potential additional willingness to pay for "circular" pork.

We find limited impacts related to the CAP subsidy shift in favor of more extensive crop production in Chapter 4. However, there are further indirect coupling channels via effects on uncertainties and risks farmers face, their access to credit, labor allocation choices, or their expectations for the future (Bhaskar and Beghin, 2009; Boulanger et al., 2017; Moro and Sckokai, 2013) that are not accounted for in the model. This limitation may lead to an underestimation of the actual impacts that could occur as a consequence of the changes to the CAP payment structure that we have explored.

The representation of policy mechanisms in CAPRI does not capture the variety of how these policies are implemented at EU member state level. In the applied model setup, the effect of long-term adjustments of primary inputs on supply and trade is reflected only to a limited extent. This could imply an underestimation of trade reactions in the long term, following changes in direct payments. In contrast, the restrictions on animal density and nitrogen application could steer innovative technologies that use fertilizer more efficiently in the long term.

Despite that our analysis in Chapter 5 allows us to disentangle a lot more heterogeneity compared to the ex-ante studies, the underlying data still does not suffice to exactly differentiate net-food producers and net-food purchasers.

We account for price transmission from international markets by including corn futures volatility as instrument in our nutrition-price analysis. However, we do not capture trade effects, trade policies, and trade openness (Amolegbe et al., 2021; Bekkers et al., 2017; Mary, 2019). Trade relations could buffer local production shocks on prices. Further research could disentangle local vs. international shocks and compare their impacts on nutrition. We do not directly include local agricultural production in our assessment to avoid potential problems related to simultaneity and multicollinearity, and due to limited data availability. Our analysis thus does not clearly distinguish impacts of food access vs. food availability on nutrition, a relevant extension to be addressed by future research.

Our underlying nutrition and price data originate from different datasets and is matched based on geolocations entailed in the two data sources. Our market price data is limited and the geo-matches might not represent the actually relevant market for each household. Nevertheless, infrastructure, market integration, and weather shocks may presumably be comparable to the true market.

1.5 Implications for policy-making and research

The studies presented in this thesis show that EU agri-food policies designed toward sustainability improvements might cause tradeoffs for other policy objectives with winning and losing actors. Consequences from regionally implemented policies can materialize around the world through trade effects and price transmissions in globalized value chains. Implications can be heterogenous and micro-level assessments are needed to disentangle these.

For policy-making, this implies the careful design of agri-food policies and their pre-assessment before implementation as unintended tradeoffs may occur. Becoming aware of the tradeoffs brings policy-making to a decisive point. However, in the politically desired transformation of the food system toward sustainability, tradeoffs will be inevitable.

Our results suggest that policy-makers need to set priorities and balance interests against each other. Some actors may best be compensated for losses to avoid sustainability tradeoffs and consistent policy packages are needed to reduce unintended consequences arising from market feedbacks.

In Chapter 2, we highlight that, besides the price effect, the implementation of food taxes can also induce an increase in awareness for food consumption impacts. This may increase consumer response beyond the elasticities in the ex-ante modelling analysis. The size of the assessed shifts toward healthy diets is well beyond the reported order of magnitude of diet changes from any single intervention in our literature review (Table 2.1). Monetary instruments alone will not suffice to reach nutrition and sustainability objectives and should be complemented by other policies.

Producers would need to cope with a reduced EU demand caused by high food tax rates. However, opportunities may arise by focusing more on quality, extensive production, and animal welfare standards. Targeted fiscal incentives may initiate product reformulations in the food industry. Supply side measures targeted at producers and the entire value chain are required in addition to further push food production towards environmental sustainability goals within the EU. A coherent policy package incentivizing the consumption, production, and trade of foods identified beneficial for sustainability and nutrition should be designed to pursue these objectives simultaneously.

Our analysis in Chapter 3 reveals that the consideration of market feedbacks results in lower environmental benefits from food waste reduction within the EU compared to the embedded impacts in the previously wasted food. Globally however, an over-proportional reduction of emissions can be achieved due to considered regional differences in emission-efficiencies of agricultural production.

If food waste feed (FWF) is available at low costs, this can be beneficial for pig farmers. Nonetheless, policy-makers need to consider that using food waste as feed is limited in its competitiveness compared to conventional feed due to its assumed low protein content. FWF could therefore require subsidization unless a price premium for circular pork is paid on the market. Furthermore, if FWF is available at a competitively low price, EU pork production and consumption might increase. This could offset intended environmental improvements.

Chapter 4 concludes that enforcing restrictions on livestock density and nitrogen application in the EU could increase pork prices in Africa. Consequently, dietary diversity could be at risk for African net consumers if animal products become less affordable. Our assessment suggests that substituting domestic production and trade flows are likely to fill the supply gap caused by EU production decreases. To what extent this potential can be used by producers in African regions depends, at least partly, on their competitiveness compared to substituting importers and on the access of their products to export markets. Moreover, increased agricultural production should best be managed environmentally-friendly to avoid tradeoffs between socio-economic and environmental goals. One often discussed attempt to reduce these tradeoffs is referred to “sustainable intensification” (Mouratiadou et al., 2021)[4].

[4] I contributed to this article during the time of my doctoral studies. It is not part of this thesis as a main chapter.

Despite increased production potentials for non-EU regions, the 2020 global economic downturn as consequence of the Corona virus pandemic and the food price increases following the war in Ukraine in 2022 reveal risks incorporated in the interconnectedness of global value chains. These observations stress the necessity to develop crisis prevention strategies that also involve measures to support domestic production of critical products for national food self-sufficiency and food security. Climate change may increase the frequency of food system instability events in the future (Dellink et al., 2017).

In order to reach environmental improvements at global level, additional measures are required to minimize leakage. Jointly reducing EU demand and supply of emission-intensive products could contribute to environmental sustainability. Implied social and economic consequences for EU farmers need to be addressed with additional instruments. However, combined measures might limit trade opportunities for low- and middle-income countries with the EU that could otherwise improve social and economic sustainability.

Our findings in Chapter 5 clearly suggest that price volatility can be transmitted from international futures to local markets in sub-Saharan Africa. This can increase stunting in children within the following year across household groups. Poor, rural, and agricultural households are affected most strongly. This stresses that also food producing households can be net food buyers and their children's nutrition may deteriorate due to higher and more volatile staple food prices, especially if these occur unexpectedly. Impacts related to other nutrition indicators turn out to be less clear. Children should therefore be protected from negative consequences of price volatility. Measures to increase resilience and to reduce transmission of futures volatility to local food systems could be a political aim. Policy-makers in various countries should increase efforts to improve food access, especially among the global poor, in order to reach SDG2, *zero hunger*, by 2030.

In this thesis, we only assess a selection of SDG impacts under consideration of food system drivers and feedbacks. These SDGs are very much interlinked to other SDGs such as SDG1, *no poverty*, SDG3, *good health*, SDG4, *quality education*, SDG5, *gender equality*, SDG6, *clean water*, SDG7*, clean energy*, or SDG14, *life below water*. Ongoing and future research will help to better understand these links and disclose further tradeoffs, but also synergies. Despite the occurrence of tradeoffs, policy-makers need to push for the actual implementation of sustainability policies to keep the SDGs within reach.

Progress towards SDGs should be stimulated by political action. Citizens can demand such policies from their representatives. However, in addition, behavioral change can also be pursued by each food system actor, including the researchers who must live up to their findings (Sanz-Cobena et al., 2020)[5].

We address synergies and tradeoffs and apply a holistic approach that integrates economic market and trade feedbacks. Heterogeneity is accounted for to the extent possible in the context of each study. With this thesis, existing research is complemented by assessments of potential future EU agri-food policies and a better understanding of food price volatility implications that are needed for the transformation to a sustainable food system.

[5] I contributed to this article during the time of my doctoral studies. It is not part of this thesis as a main chapter.

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Chapter 2
Paying the price for environmentally sustainable and healthy EU diets[*]

Abstract. We review consumer-side interventions and their effectiveness to support a transition to healthier and more environmentally sustainable diets and identify taxes/ subsidies as relevant instruments. To quantify the scope of necessary tax levels to achieve dietary recommendations on EU average, we apply three established economic models. Our business-as-usual food intake projections stress the need for policy intervention to resolve continued divergence from nutrition guidelines. Our findings suggest that food group specific taxes are effective in reaching nutrition and environmental sustainability targets. However, considerable tax levels are required to achieve the targeted consumption shifts, inducing a discussion about alternative policy designs and current model limitations. A coherent policy

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package is suggested to approach nutrition and sustainability objectives simultaneously.

Keywords: greenhouse gas emissions; sustainable diets; consumer taxes; nutrition guidelines

2.1 Introduction

Malnutrition is growing across European adults with more than half of the population already being overweight or obese (Marques et al., 2018). Average adherence to dietary recommendations is low (Mertens et al., 2018) and the number of diet-related cardiovascular deaths has increased in the recent past (Meier et al., 2019). Unhealthy diets are one of the main determinants for overweight and related diseases while the intake of important micronutrients is often deficient (Elmadfa and Meyer, 2009).

In the absence of a common European Union (EU) food policy, the Sustainable Development Goals (SDGs) become the effective shared policy commitment at EU level to achieve food security, improve nutrition, and promote sustainable agriculture (SDG2) (Fabbri, 2017). The food system is concerned with further aspects related to social, environmental and economic sustainability (Rutten et al., 2018). The future objectives of the EU Common Agricultural Policy (CAP) overlap with several SDGs (Box 1). Agricultural transformation has great potential to contribute to environmental sustainability objectives as the sector is responsible for 10% of EU overall greenhouse gas (GHG) emissions in 2017 (EEA, 2019) and for reactive nitrogen (N) losses to the biosphere which pose a risk to the quality of air, soil and water (Sutton et al., 2011). Changes in EU dietary patterns will likely have significant implications with respect to achieving several SDGs and thus to contributing to the shared commitment adopted with the 2030 Agenda for Sustainable Development by all United Nations Member States (UN, 2015).

Box 1: Proposed objectives of the future CAP overlap with several SDGs.

Selected CAP objectives (European Commission, 2020)	**Related SDGs (UN, 2015)**
Climate change action	**SDG13** Take urgent action to combat climate change and its impacts
Environmental care	**SDG15** Protect, restore and promote sustainable use of terrestrial ecosystems (…) and halt and reverse land degradation (…)
Preserve landscapes and biodiversity	**SDG15** Protect, restore and promote sustainable use of terrestrial ecosystems (…) and halt biodiversity loss
Protect food and health quality	**SDG2** (…) Achieve food security (…), **SDG3** Ensure healthy lives (…)
Vibrant rural areas	**SDG11** Make human settlements inclusive, safe, resilient and sustainable
Rebalance power in the food chain	**SDG9** (…) Promote inclusive and sustainable industrialization and foster innovation
Ensure fair income	**SDG8** Promote (…) decent work for all, **SDG10** Reduce inequality within and among countries

Given the observed gap between recommended and actual intakes in EU member states (Mertens et al., 2018), we focus on the scope for steering diets through consumer policies to support an integrated approach to healthy diets and environmentally sustainable food systems in the EU. The novelty of our approach is to combine the implementation of a dietary target derived from nutritional insights with what is deemed effective given the intervention evidence found in the literature (section 2). We apply three economic models that are able to incorporate the overall socio-economic context and return food system's implications of such diet policies. We enforce two kinds of dietary targets, a healthy dietary pattern and a reduced total calorie intake (section 3). The models solve for the necessary price changes to reach these dietary shifts at EU population level. We discuss the resulting price changes and evaluate these in terms of their efficiency in reaching nutrition and environmental sustainability objectives compared to the business-as-usual (BAU) development without food policy intervention (section 4 and 5).

2.2 Effectiveness of interventions for dietary changes

2.2.1 *Literature review and freedom of choice assessment*

While there is already an extensive body of literature on how dietary changes may serve health and environmental objectives (e.g. Springmann et al. (2018, 2017), Tilman and Clark (2014), Tukker et al. (2011), Westhoek et al. (2014), Wolf et al. (2011)), these existing modelling studies tend to neglect the discussion about the required instruments. We target our contribution on finding more solid ground for defining policy instruments for the large-scale behavioral change demanded from a future European food policy. Therefore, we place diet policies into perspective of established theories of behavioral change from the public health domain and structure a review of existing evidence on the effectiveness of diet interventions.

Instruments that rank high from a political economy point of view as they allow freedom of choice may not be sufficient in terms of achieving the desired large-scale diet transformation. Griffiths and West (2015) propose a balanced scheme for ranking public health interventions under consideration of their impact on consumption choice autonomy. Interventions can either compromise or enhance (e.g. via information provision) the liberty of the consumer. We extend this scheme by the freedom of supply chain actors to assess the desirability of health-motivated interventions from a food systems perspective, reflecting both demand- and supply-side autonomy (Table 2.1).

Numerous review studies assess dietary, health and welfare impacts as well as strengths and weaknesses related to different food policy types (e.g. Brambila-Macias et al. (2011), Capacci et al. (2012), Garnett et al. (2015), Hyseni et al. (2017), Mazzocchi (2017), Mozaffarian et al. (2018), Sassi et al. (2009), Thow et al. (2014)). Due to the divergence in study types, variations in policy set-ups and regarding the consideration of substitution and distributional effects, the results of these studies differ and are partly even contradictory.

Mazzocchi (2017) reviews evidence on the effectiveness of different types of health and nutrition policies implemented at national level. While information measures are most prevalent, also school food interventions and more restrictive policies like labelling or bans are increasingly taken up. Hyseni et al. (2017) find that multi-component and price interventions as well as product reformulations appear to be effective policies in terms of stimulating healthier eating patterns and perform better than food labelling or food restrictions.

Darmon and Drewnowski (2015) discover a tendency for healthy diets to be relatively expensive. Economic instruments adjusting food prices based on their contribution to healthy diets could rebalance relative price levels. Brownell et al. (2009) identify imperfect information, time inconsistent preferences and externalities as food consumption related market failures. The occurrence of these market failures can - to a certain extent - justify government intervention and the restriction of agents' freedom of choice. Taxation and subsidization are market-based interventions that can be applied to internalize externalities and to resolve occurring market failures.

Thow et al. (2014) review 38 studies analyzing the effectiveness of taxes and subsidies on food consumption and find a consistent effect on improved intakes in terms of obesity and chronic disease prevention. Nutrition-targeted taxes have become a popular measure in the recent past, due to their comparative effectiveness in influencing consumption behavior (Mazzocchi, 2017).

We summarize the evidence on diet change by intervention in Table 2.1 based on studies that review the effectiveness of various instrument types. The most preferred options from a freedom of choice perspective show limited impact, while often modelled taxes and subsidies can be effective but risk undesirable substitution effects (Garnett et al., 2015). Some non-price interventions reveal promising effects, however, dependent upon their implementation, the intervention setting, or restricted to a target group. Large-scale impacts of these measures are difficult to gather and long-term effects are rarely investigated. Despite that the assessed interventions target consumers' food consumption behavior directly, they restrict freedom of choice of supply chain actors in nearly all cases. The implementation of consumer interventions affects the producer surplus which can be interpreted as impacts on suppliers in marketing activities, product formulation and in selling their products.

We conclude that taxes and subsidies can be effective instruments to steer diets. Various kinds of food tax modelling studies can be found in the literature. Most of these studies focus on the effects on nutrition and health (e.g. Nnoaham et al. (2009), Springmann et al. (2018), Veerman et al. (2016)). Some studies model the impact of GHG emission taxes on health (Briggs et al., 2013; Springmann et al., 2017). A thorough analysis of impacts on environmental sustainability arising from the implementation of nutritionally motivated financial instruments is so far missing.

Table 2.1 Intervention effectiveness – Evidence of diet change.

Freedom of consumer choice

Freedom of supply chain actor choice

Intervention	Brambila-Macias et al. 2011	Capacci et al. 2012	Garnett et al. 2015	Hyseni et al. 2017	Mazzocchi 2017	Mozaffarian et al. 2018	Sassi et al. 2009	Modelling instruments
Information campaigns/ dietary guidelines	Absent for short-lived interventions, awareness raised	Suggestive, small	Unclear long-term effects, awareness increase	Small effect size, uncertain long-term effects	Strongly effective	Limited overall direct effectiveness	+18.4g V&F	Preference shifters
Compulsory information on products (e.g. labelling)	Uncertain, more promising for simple labels, contributing to informed choice	Mixed	Inconsistent consumer responses	Effective, but interpretation difficulties	Suggestive, slightly effective	Mixed, effectiveness depending on knowledge and attention	+9.9g V&F -0.4% fat%E	
Food advertising regulations	Weakly effective	Suggestive, uncertain long-term	Significant	Appears effective	Suggestive, short-term, effective if comprehensive	Sustained, effective if implemented across formats	+0.4% fat%E	
Ensuring choice availability (e.g. school food programs)	Effective, limited to target group	Suggestive	Positive impacts on diets in intervention setting	Modest to small effect size, uncertain long-term effects	Suggestive, strongly effective in intervention setting	Sustained, effective	+38g V&F -1.6% fat%E	
Financial (dis-) incentives through taxes/ subsidies	Effective, but intrusive and potentially regressive	Suggestive, mixed, uncertain regarding distributional impacts	Combinations of taxes and subsidies effective	Consistently effective, diet change price dependent, substitutions can offset improvements	Suggestive, strongly effective	Effective, most promising as combination of incentives and disincentives	+8.6g V&F -0.8% fat%E	Taxes/ subsidies
Restricting/ eliminating choice	Seems effective, limited evidence	Suggestive	Positive impacts on diets in intervention setting	Appears powerful, but neglected	Suggestive, mixed effects	Promising, but neglected	-	Trade/ production quota

Note: The presented effectiveness statement follows the terminology used in the respective study. We rank policy instruments based on the balanced intervention ladder by Griffiths and West (2015) extended by supply chain actor freedom of choice and review selected literature regarding the evidence of diet change. Related modelling instruments are linked to the interventions. (V&F = vegetables and fruits, fat%E= % as total energy from fat).

2.2.2 *Modelling dietary changes*

The spectrum of available modelling instruments to simulate diet interventions is limited. In Table 2.1 we link typically applied modelling instruments to the discussed interventions. For some interventions, there is insufficient knowledge to model their quantitative relationships. In these cases, the result of the intervention (i.e. the changed diet) is modeled with a 'preference shift'. Preference shifts are usually modelled as costless changes in consumer behavior, which means that the parameters in the demand system are exogenously changed to impose the desired behavior. Preference shifts remain silent on how these changes in behavior can be achieved and ignore the cost of the measures behind it. Financial incentives are implemented by taxes and subsidies. The hereby targeted behavioral change is achieved endogenously driven by resulting price adjustments. A restriction of product choice in the market could be modelled as production and trade interventions (e.g. quotas) reducing the products available in the market.

In the study at hand, we focus on tax- and subsidy-based instruments to achieve diet changes in line with nutrition recommendations. Our literature review indicates that these instruments can be effective and their model implementation allows to identify the necessary scope of price changes for the envisaged consumption shifts.

2.3 Methods

2.3.1 *Model approach*

We apply three established global economic models to take advantage of individual model strengths in our analysis and to reduce uncertainties inherent to modelling studies. The Common Agricultural Policy Regionalized Impact (CAPRI) modelling system is a comparative-static, partial equilibrium agricultural sector model developed for policy and market impact assessments from global to regional and farm type scale. The modelling system contains a spatial, non-stochastic global multi-commodity model. It is defined by a system of behavioral equations differentiated by commodity and geographical units. Food consumption is derived at country level based on FAO food balance sheets and Eurostat (Britz and Witzke, 2014). Consumer demand is based on generalized Leontief expenditure functions (Ryan and Wales, 1999). Resulting indirect utility functions depend on prices and increase in income. The Global Biosphere Management Model (GLOBIOM) is a partial equilibrium model that covers global agricultural, bioenergy, and forestry sectors (Havlík et al., 2014; Frank et al., 2015). Prices are endogenously determined at the regional level to establish a market equilibrium to reconcile demand, domestic supply and international trade. Land and other resources are allocated to production and processing activities following the objective to maximize the sum of producer and consumer surpluses. The Modular Applied GeNeral Equilibrium Tool (MAGNET) is a multi-regional, multi-sectoral, applied general equilibrium model based on neo-classical microeconomic theory (van Meijl et al., 2006; Woltjer and Kuiper, 2014). The core of MAGNET is an input-output model, which links industries in value added chains from primary goods, over intermediate processing stages, to the final assembly of goods and services for consumption. On the consumption side, a dynamic constant difference of elasticities expenditure function allows for changes in income elasticities in response to changes in model variables (e.g. gross domestic product (GDP)). While MAGNET and CAPRI use the 'Armington (1969) approach' to represent international trade and to differentiate imported from domestically produced products, in GLOBIOM imported and domestic products are assumed homogenous. Further differences between the models exist regarding the definition of consumer prices and the usage of cross-price elasticities.

Technically these models are all able to impose a desired consumption pattern. The implications, however, vary across models. CAPRI and GLOBIOM are partial equilibrium models implying there is no feedback loop from changes in the agri-food system to household incomes and they capture food related household expenditures only. Simulated choices between products are driven by changes in product prices and consumer preferences. MAGNET uses a similar approach but, being a general equilibrium model, total household income is affected by changes in the agri-food system. Furthermore, MAGNET endogenously models non-food expenditures and covers processed food explicitly. In contrast, CAPRI and GLOBIOM express demand for food products in primary equivalents (Appendix A, product mapping of target foods).

2.3.2 *Scenario design*

The BAU reference scenario assumes a continuation of the global food system's past development. Among the macro drivers, population and GDP have the most direct impact on consumer decisions simulated in the models. Global population and GDP developments are aligned with the widely used Middle of the Road projections in the Shared Socioeconomic Pathway (SSP2) (see Kc and Lutz (2017), Appendix B). These drivers have a direct effect on consumer purchases, per capita food availability and accessibility. All scenarios are run with global coverage, while the diet intervention is limited to the EU population.

In our model assessment we combine two types of tax scenarios, one focused on food groups and the second on total calorie intake. This way we address concerns on both nutritional adequacy and overweight. The food-based approach is chosen because increasing evidence points out that specific foods have a substantial role in the prevention of chronic diseases (Mozaffarian and Ludwig, 2010). Mertens et al. (2018) show considerable variation in food patterns across four European countries and a low adherence to food based dietary guidelines, with a wide variation regarding dietary patterns within populations. Using population averages for the scenario definition thus has limitations.

For the scenario definition, we focus on three groups of food products which are important markers of diet quality: vegetables and fruits, red and processed meat, and sugar (Mertens et al., 2018). Population adherence to fruit and vegetable intake recommendations of at least 200 g/day is low for Denmark, France and Czech Republic. Mean intakes of red and processed meat exceed the recommended upper limit of 71 g/day for these countries (Mertens et al., 2018). Red and processed meat intakes are related to increased risks of cardiovascular disease, diabetes and colorectal cancer

(Ekmekcioglu et al., 2018). In Denmark, Czech Republic and France mean intakes of 108-224 ml/day of sugar sweetened beverages exceed the suggested intake limit of 71 ml/day (Mertens et al., 2018). A reduced sugar intake aligns with the WHO target to reduce obesity by decreasing added sugars, since sugar is related with risks of diabetes and increases in body mass index (BMI) (Singh et al., 2015; WHO, 2000). On EU average about 53% of the adults are overweight (BMI $\geq$25 kg/m^2) of which 16% count as obese (BMI $\geq$30 kg/m^2) in 2014 (Marques et al., 2018). Overweight and obesity are the result of an imbalance between energy intake and energy use for maintenance, growth and physical activity. Due to missing data and model representation we have to ignore physical activity while acknowledging its importance. Working towards a population level policy which is rough by design, we average variations in age, weight, physical activity, and sex. Since we are missing information on the distribution of the BMI among the obese, we approximate a 10% average calorie reduction target based on the energy requirements provided by FAO (2004) in order to reach an average EU BMI below 25 kg/m^2 also among the overweight population groups (Appendix C). Table 2.2 summarizes the diet scenario specifications. For simplicity we assume a linear implementation over the projection period until 2050. We derive the envisaged food pattern changes based on current divergencies to recommended consumption quantities stated by Mertens et al. (2018). As these food intake recommendations are maximum and minimum suggestions, we accept their potential overfulfillment in the scenarios for some of the countries. The dietary targets are set in a way that they are deemed feasible given past trends in European diets and achievable based on observed current diets of population subgroups. We run the food pattern and total calorie intake changes in a combined mode and perform a sensitivity analysis testing both scenario elements which allows us to disentangle the effects of each component.

Table 2.2 Diet scenario specification for EU average intakes based on recommended % consumption change in 2050 relative to 2010.

Diet target	%-change	Scenario	Sensitivity scenarios
Vegetables & fruits (V&F)	+100	Food pattern & BMI<25	Food pattern
Red & processed meat (REM)	-50		
Sugar (SUG)	-50		
Total calories	-10		BMI<25

Note: Total calorie intake is not fixed in sensitivity scenario 'Food pattern'.

We impose these recommended consumption changes to the models and leave the respective prices to be changed endogenously by the models. We interpret the resulting price changes as consumer taxes. However, if the attempt of introducing price shifts to attain these demand changes reaches the feasibility boundaries of the models, an exogenous preference shift is introduced instead for the respective dietary adjustment. This is the case in MAGNET to increase the intake of vegetables and fruits and in CAPRI to achieve the sugar reduction target (Appendix B, supplementary model information).

2.3.3 *Indicators*

Food system implications of consumer interventions are investigated on the basis of food demand, expenditure and price changes. To assess nutrition impacts at the food intake level we establish a top-down link between one of the economic models, MAGNET, and the FoodEx2 intake data from three country-level surveys used in the diet model SHARP (Mertens et al., 2017). The other two economic models have not been linked to the intake data due to their different food representation in primary equivalents and as the FoodEx2 data do not contain recipe information on primary content of products needed to connect the databases. MAGNET does capture processing of food in a very aggregate manner, while the intake surveys register food items at a high level of detail. We thus define the best possible match of products between the aggregate food categories of MAGNET to the 955 FoodEx2 consumer products (including processed products with mixed ingredients) in the SHARP database (Mertens et al., 2019) with an obvious loss of detail at the macro level. The economic models refer to food demand based on average food availability. Despite a deduction of food losses, inedible parts and approximate food waste shares, a divergence between the available food and its actual intake remains (see Appendix B for further details). Given these considerations we rely on the economic models for changes in environmental sustainability, production, demand and trade, while exploiting the actual intake data in the MAGNET-SHARP database link to get a more precise assessment of nutrition metrics. To assess the nutrition improvement arising from these consumption changes, we calculate the Nutrient Rich Diet score based on 9 qualifying and 3 disqualifying nutrients (NRD9.3) following the approach used by van Kernebeek et al. (2014) with a score of 1 representing complete adherence to nutrient recommendations. Demand changes following from the scenario implementations are provided by MAGNET to the SHARP database. Based on the developed product mapping, these changes are translated to the differentiated product range in the SHARP database to derive the nutrient indicator for each scenario at country level. It should be noted that the SHARP database currently only covers three EU member states and has no coverage outside the EU. In order to assess environmental sustainability, we compare the resulting changes in non-CO2 GHG emissions from agricultural production and trade in the EU and the rest of the world. In addition, we compare N fertilizer application amounts and N surpluses across scenarios.

2.4 Results

2.4.1 *Food demand, expenditure and nutrition*

EU average GDP per capita is projected to grow by about 75% until 2050 in comparison to 2010 levels in the BAU scenario. EU members with below EU average incomes in 2010 are projected to slowly converge towards Western European income levels, reflected in higher per capita growth rates.

The income increase in the EU does not imply an equally strong increase in food expenditures.

EU household food expenditures do not change strongly in the BAU scenario from 2010 to 2050 (USD/cap/day +0.5 in CAPRI, -0.01 in GLOBIOM, +0.2 in MAGNET) due to low price and income elasticities. The diet scenarios show an increase in EU household food expenditures. As presented in Figure 2.1 achieving two changes simultaneously, diet pattern and total calorie reduction, induces a strong increase in EU average food expenditures (USD/cap/day +20 in CAPRI, +3.3 in GLOBIOM, +6.5 in MAGNET compared to BAU 2050). CAPRI reacts with a stronger increase towards the various simultaneous constraints which exceeds the sum of expenditure increases of each scenario component as shown in the sensitivity analysis. Rising expenditures raise concerns with respect to the affordability of food. Food, however, is only a minor part (11% in 2017) in the average EU household budget (Eurostat, 2019) and this share is expected to decrease further. In the absence of any diet specific intervention (BAU) the share of food in total expenditures is projected to nearly halve by 2050 driven by expected EU GDP growth and population decline raising per capita income. Enforcing the shifts towards recommended diet patterns increases food expenditures as expected, but the share of household budget needed for food remains moderate (up to 12.4% across models and scenarios) as household income is projected to rise much stronger over time.

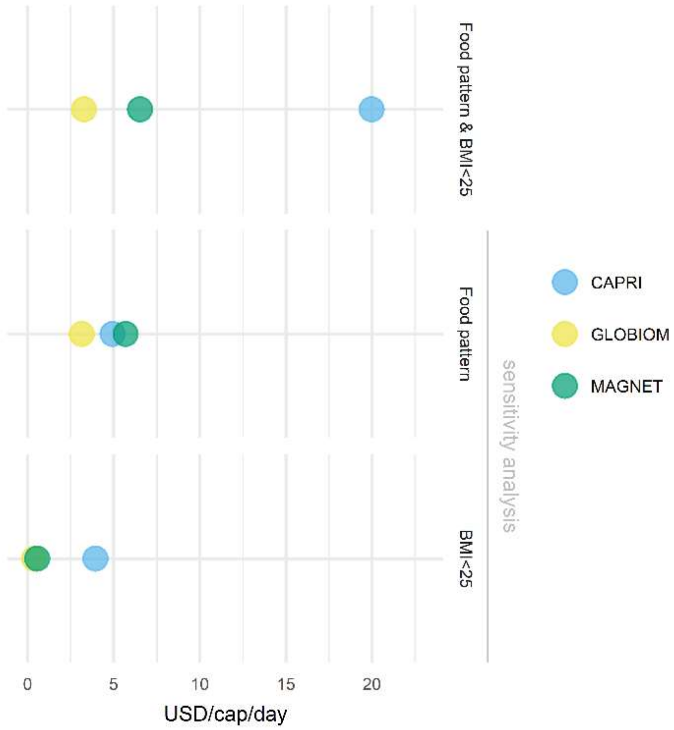

Figure 2.1 Absolute change in EU food expenditure in USD/cap/day compared to the business-as-usual in 2050.

For red and processed meat, a consistent increase of average EU household purchases is projected until 2050 without dietary policy intervention (Figure 2.2). The average EU demand for vegetables and fruits declines slightly. The projected sugar consumption is more divergent across models with both increases and decreases projected.

We observe considerable differences in the BAU projections regarding per capita consumption developments of the target food groups across models and EU member states. Moreover, calorie accounting diverges between models given differences in product representation, underlying data sources, model calibration and post-model processing (Appendix B). Despite the differences, all models support the conclusion that without interventions directed at consumer purchases and dietary habits, the EU will miss the dietary recommendations on average in 2050 and even deteriorate compared to 2010 (Figure 2.2).

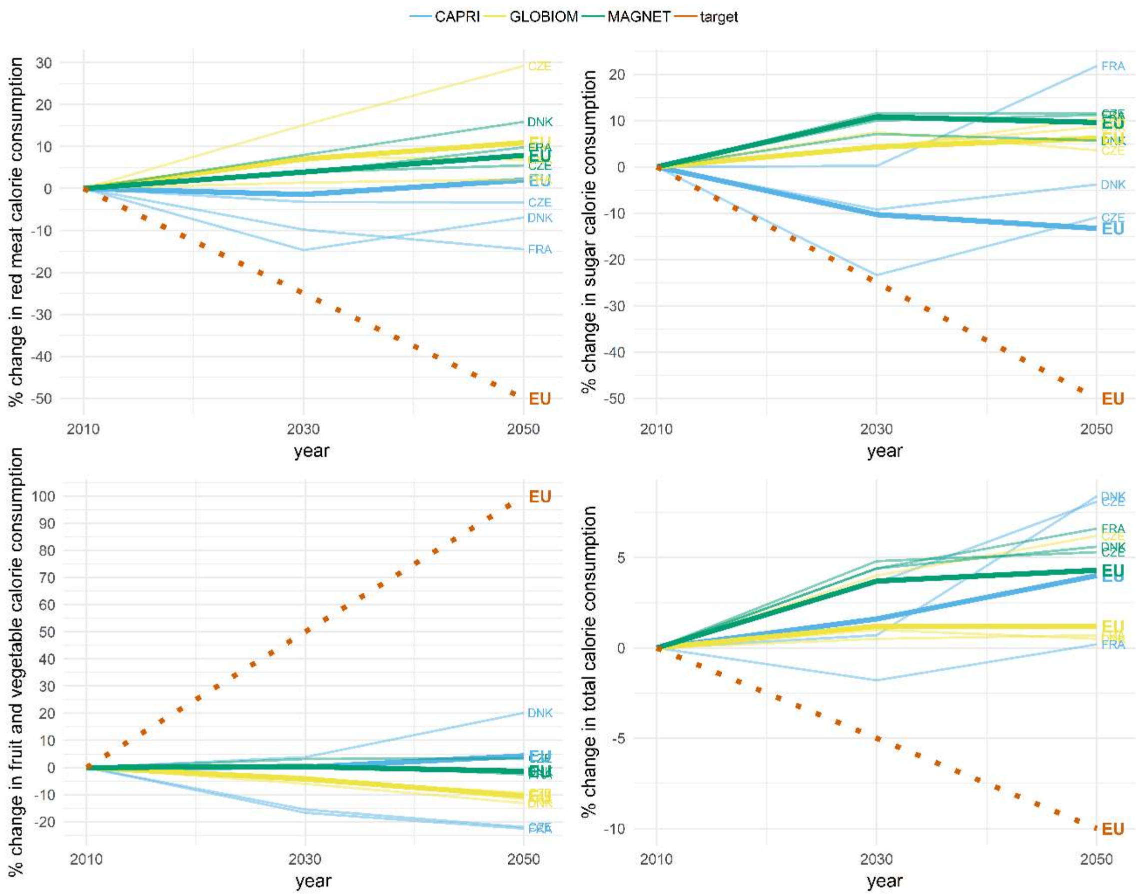

Figure 2.2 Percentage consumption changes in the business-as-usual for 2030 and 2050 relative to 2010.

Note: Projections are displayed for the EU average and three EU member states (France (FRA), Czech Republic (CZE), Denmark (DNK).

The dietary targets are implemented on EU average level. On member state level this results in diverging consumption impacts (Appendix B, D). A consumption shift to non-targeted substitute foods is moderate in MAGNET. The scope of substitutions is limited in GLOBIOM as cross-price elasticities are not captured. CAPRI results project strong substitutions with increases in poultry meat consumption resulting from the price increase in red meat. Considerable price changes are required to achieve the calorie intake reduction and the food pattern shifts as shown for the target food products in Figure 2.3. Tax rates of up to several thousand percent for sugar, and red and processed meat are necessary to move consumption 50% away from simulated 2010 consumption quantities in the price- and elasticity-driven modelling systems. For example, assuming a sugar consumer price of 0.8 USD/kg, a tax of 1500% would result in a new consumer price of 12.8 USD/kg. The sensitivity analysis shows that the BMI<25 scenario alone allows the models some leeway to reach the calorie reduction target and that the price increase is largely driven by the taxes on the target food groups.

Moreover, the improvements in nutritional quality represented by the NRD9.3 follow largely from food group specific taxes across the three assessed EU member states (Figure 2.4). The reached nutrition scores lie close to the upper boundary of the range of nutritional differences currently observed within these populations and thus imply a considerable improvement of nutritional quality if achieved by population average (Table 2.4 in Appendix B). The simulated tax on total calories alone does not achieve substantial nutrition advances according to the model results, nor does it add additional achievements in the combined tax scenario. Despite the enforcement of recommended dietary targets no perfect score is reached. This is largely due to the top-down MAGNET-SHARP linking, where consumer responses are modelled in MAGNET for 17 aggregate food sectors and then mapped to the 955 FoodEx2 categories. Lacking consumer responses to price and income changes at the FoodEx2 product level, there is no scope for substitution at this finer level which is expected to yield a larger change in nutrient intake due to the broad variety of products associated with a single MAGNET sector.

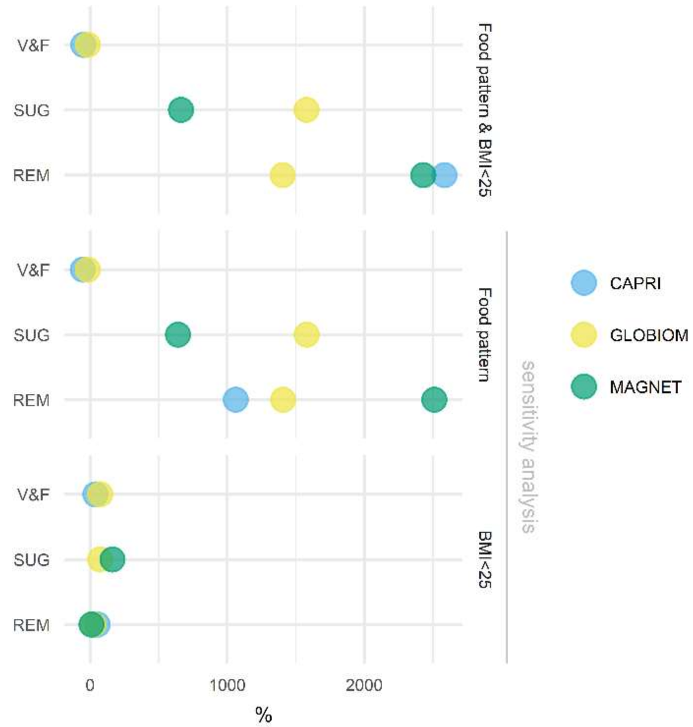

Figure 2.3 EU consumer tax rates (%) for targeted food products in 2050.Note: Required subsidies to double vegetable and fruit (V&F) intake are comparably moderate, while consumer prices would need to increase strongly to halve red and processed meat (REM) and sugar (SUG) demand or to reduce total calorie demand on top.

As part of the sensitivity analysis, total calorie intake reduction to achieve a decline in overweight prevalence is enforced separately in the BMI<25 scenario. The results show that without this explicit target, the food pattern adjustment alone (Sensitivity scenario Food pattern) only reduces total calorie intake in one of three model projections (%-change in total calorie intake +10 in CAPRI, -7 in GLOBIOM, +7 in MAGNET in the food pattern scenario).

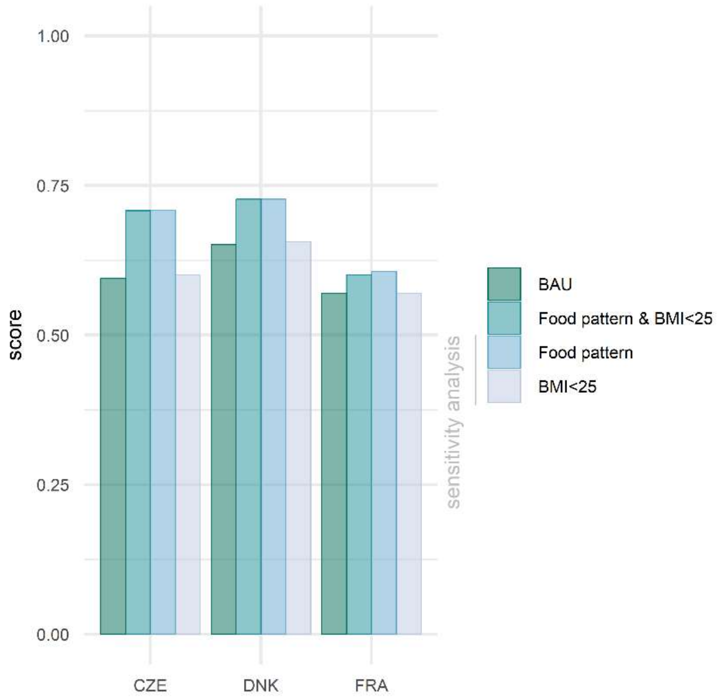

Figure 2.4 NRD9.3 for three EU member states (Czech Republic (CZE), Denmark (DNK), France (FRA)) in 2050 based on MAGNET-SHARP.Note: BAU = Business-as-usual.

2.4.2 *Environmental sustainability impacts*

In 2011 the European Commission released a roadmap towards a low carbon economy proposing potential reductions of agricultural GHG emissions by up to 49% until 2050 compared to 1990 emission levels which is equivalent to a reduction of about 267 Mt CO2eq (European Commission, 2011). In 2018, the European Commission even increased its ambitions aiming for a climate neutral economy in 2050 (European Commission, 2018). Between 1990 and 2017, 20% of EU agricultural GHG emissions could be reduced (EEA, 2019). However, since 2011 EU agricultural emissions have been increasing by 3.6% until 2017 (EEA, 2019).

GLOBIOM and MAGNET model results show a substantial decline in EU agricultural non-CO2 GHG emissions if the diet taxes are applied. EU emission savings arise dominantly in the livestock sector. The reductions appear to be comparatively small in the CAPRI results. The comparison to agricultural emission savings in the rest of the world (Figure 2.5) reveals that strong emission reductions are suggested by CAPRI as well, only that these occur mostly in non-EU regions. These differences are reflected in agricultural production and trade pattern changes and are due to different trade responsiveness between models. Therefore, also N surpluses occurring from EU agricultural production are reduced only marginally as consequence of the diet scenarios in CAPRI. Fertilizer application is hardly affected in the CAPRI projection, whereas the decline in agricultural production goes in line with a strong reduction of N fertilizer usage according to GLOBIOM (see Appendix E for further details). Disentangling the tax effects by sensitivity scenarios reveals that reducing total calorie intake alone (BMI<25) causes comparably small reductions in related environmental impacts.

The drastic consumption changes we enforce to follow dietary guidelines on EU average imply diverse consequences for EU agricultural production in the models. In MAGNET, the EU demand change translates to a domestic production adjustment. A similar observation is made for the CAPRI results, but the effects are much smaller due to the aforementioned stronger trade response. Agricultural production in GLOBIOM decreases strongly for commodities directly affected by taxes. The production of vegetables and fruits however also decreases slightly in GLOBIOM despite the doubling of domestic consumer demand for this food group. This decrease is driven by reduced production of roots and tubers being part of this category which are largely used for animal feed and decline in line with decreasing livestock production. This is also reflected in the slightly decreasing EU imports of vegetables and fruits in the GLOBIOM results.

Despite this exemption, similar import changes occur across models. Products for which EU demand drops are imported less, while imports of vegetables and fruits increase. Strongly increasing exports of red meat in the food pattern scenarios explain that emission reductions occur in EU trading partner countries in the CAPRI results. Emission reductions are in that sense “exported”.

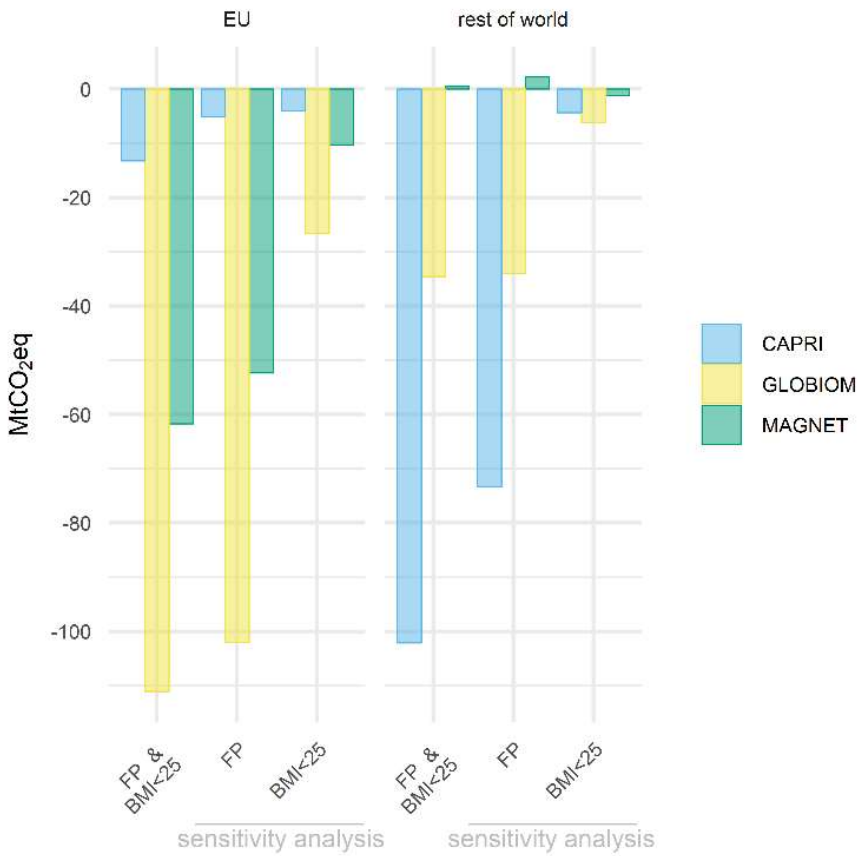

Figure 2.5 Absolute change in non-CO2 greenhouse gas emissions from agricultural production in the EU and in the rest of the world compared to the business-as-usual in 2050. Note: FP = Food pattern.

In summary, strong demand reductions for sugar, and red and processed meat affect the respective producers of these products - either in the EU or in countries that are increasingly importing European products. A combination of a general calorie tax and specific food group taxes does not improve nutrition considerably more than the food pattern intervention alone, while emissions are reduced slightly more. The impacts on most indicators are not found to be strictly additive when imposing the food pattern and total calorie changes jointly as these are presenting additional constraints to our non-linear models.

2.5 Discussion and conclusions

The objective of this research was to apply a multi-modelling approach in order to determine the required level of consumer taxes and subsidies to steer recommended dietary shifts and to compare their effectiveness in contributing to EU nutrition and environmental sustainability objectives. Our findings show that food group taxes contribute effectively to these objectives. Total calorie intake reduction does not automatically end up in a more balanced diet since calories are reduced where it is cheapest in the applied models. Even with food group targets though, we do not perfectly hit the nutrition objectives by 2050. In part this is due to limitations of the top-down linking in this application, as discussed above. More generally, micro-managing nutrient intake (by consumers or governments) may be challenging with nutrients being supplied in varying combinations through a wide variety of products. Also, care needs to be taken that changes in targeted food groups are balanced in their nutritional implications. Despite that overconsumption of certain foods represents a health risk, moderate intake amounts can be a source of valuable nutrients like protein and iron in the case of red meat.

High taxes are imposed to achieve substantial changes in food purchases and these may push the models beyond the range of validity of their implemented consumer price responsiveness. The price elasticities are estimated based on observed data (for further details see Appendix B). The large-scale diet shift, however, deviates strongly from the model calibration points and likely implies too rigid model behavior. Therefore, the resulting tax levels should be interpreted with caution, focusing rather on the order of magnitude than on the exact values. Nevertheless, also Springmann et al. (2018) find that a price change of more than 100% is needed in high-income countries to reduce processed meat intake by 25%. Whether in reality comparably high tax rates would be necessary to reach substantial demand changes remains speculative as validated price elasticities for this size of demand shift are missing. Changes in preferences and substitution behavior towards vegetarian diets would likely require less drastic price incentives. Increased awareness due to the implementation of the fiscal diet interventions may increase consumer response beyond the elasticities in the current modelling analysis. Overall, the effectiveness of non-price interventions at large scale is difficult to measure as the literature review in Table 2.1 suggests. Further research on the interactions of price and non-price measures is needed. Still, our results indicate that likely more ambitious interventions are required to reach nutrition and sustainability objectives than those often under public discussion.

High tax rates as suggested by the model simulations raise concerns regarding the intervention design. Alternative to our approach, a budget-neutral tax design could be chosen balancing subsidies and taxes in a way that consumers following a healthy diet are not worse off (e.g. Briggs et al. (2013)). Also, a redistribution of tax revenues via income-dependent or lump-sum transfers like recurrently discussed and partly implemented for carbon taxes (e.g. Carattini et al. (2018), Klenert and Mattauch (2016)) could be an option to reduce social equity concerns. The models rely on a single representative consumer for each country or region and thus cannot address the food accessibility of poor subgroups in the population. Additional assessments using micro level data would be needed to address these distributional issues, while also taking differences in diets and thus exposure to diet-related health risks into account.

In our scenario design broad food group diet targets are defined as percentage changes and implemented at EU level. As dietary patterns and obesity rates diverge also between countries, a uniform relative diet target across EU member states might not be the most efficient way to achieve healthy diets on a regional level as some countries could do with less stringent targets if their current diet is healthier than the EU average.

Reducing total calorie intake alone does not go along with decreased demand for the most emission intensive products. The food pattern taxes though clearly promise a contribution to reducing agricultural GHG emissions - either directly from EU production or from reduced production in trading partner countries. It should be noted that strong consumer price changes might affect food waste behavior and thus the intake share of products purchased. This could result in further environmental benefits which are not accounted for in the present study.

Model results differ with respect to whether EU producers or producers in trading partner countries would be affected mostly. Opportunities for increasing profitability may arise by focusing more on quality, extensive production, and animal welfare standards (Dawkins, 2017). Fiscal incentives may also initiate product reformulations in the food industry and thus change the product line offered to consumers (Vandevijvere and Vanderlee, 2019).

The size of the envisaged shifts towards healthy diets is well beyond the reported order of magnitude of diet changes from any single intervention in our literature review. Acknowledging the previously mentioned modelling limitations, it nevertheless appears that monetary instruments alone will not suffice in order to reach nutrition and sustainability objectives. Complementary measures able to change behavior of large consumer groups are needed alongside price signals. These could be a mix of the non-fiscal interventions contrasted in Table 2.1 like information campaigns, product labelling or target group specific interventions to increase awareness, acceptability and willingness of consumers to change to sustainable and healthy diets. Future research could reveal further insights into how large and persistent dietary changes can be achieved at population level. Supply side measures targeted at producers and the entire value chain are required in addition to further push food production towards environmental sustainability goals within the EU. A coherent policy package incentivizing the consumption, production and trade of certain foods identified beneficial should be designed to reach nutrition and sustainability objectives simultaneously and thereby restricting freedom of choice to the least possible extent.

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2.7 Appendix

2.7.1 *A. Product mapping*

Table 2.3 Product mapping for groups of food products targeted in the diet scenarios by model.

	CAPRI*	GLOBIOM*	MAGNET#
Vegetables & fruits	Tomatoes Other vegetables Apples Other fruits Nuts Citrus fruits Grapes Olives	Potatoes Sweet potatoes Pulses	Vegetables+ Fruit Nuts Edible roots and tubers Pulses
Red & processed meat	Pork Beef Sheep and goat meat	Pork Beef Sheep and goat meat	Cattle Sheep, goats, horses Pig & other animal products Processed meat - beef Processed meat - sheep, goats, horse Processed meat - poultry Processed meat - pork
Sugar	Sugar	Sugar beet and cane	Sugar+

Note: *Products in primary equivalents; #Products in dollar values; +amounts of fruit & vegetables and sugar consumed via processed food are captured when assessing private consumption but not targeted via taxes on the single category of processed food.

2.7.2 *B. Supplementary model information*

Three established economic models are applied in this study to assess required price changes for reaching nutritionally motivated diet changes on EU level and their implied economic and environmental impacts:

- CAPRI (https://www.capri-model.org/)
- GLOBIOM (https://www.globiom.org)
- MAGNET (https://www.magnet-model.org/).

The business-as-usual (BAU) scenario is based on the "REF0" scenario in Frank et al. (2018). The shared scenario assumptions build on GDP and population developments from SSP2 in the IIASA SSP database (https://tntcat.iiasa.ac.at/SspDb/). Despite that long-term GDP and population projections are aligned and input data such as consumption trends or yield shifts are exchanged between the models, differences remain in the results. These arise from divergencies in model databases and underlying assumptions. The models are calibrated using historical data and future trend projections of various other sources regarding certain parameters. In some cases, problems with the historical data have created surprising kinks in model projections, such as sugar consumption in Czech Republic. In the CAPRI database Czech sugar consumption is strongly declining after 2010 up to 2014 while CAPRI projects a recovery and monotonic increase thereafter. The Czech ex-post data in the database may be questionable but they imply that what looks like a kink in 2030 is in fact a correction of short run fluctuations. If we had taken a seven-year average around 2010 as our starting point instead the CAPRI projections for Czech sugar consumption would have looked monotonic. Furthermore, inflection points can arise due to changes in macro drivers (population and GDP) in the 2010-2030 period versus the 2030-2050 period. Interpolating these points would provide a smoother picture but changes in trends for certain countries would remain. Based on each models' database the common drivers in all three models are assumptions of neoclassical economic theory on demand and supply governed by prices.

Demand elasticities in the models are informed by the literature for each of the models as shown in Table 2.4. Average EU expenditure and own-price elasticities for the target products give an impression of direction and magnitude. The elasticities are used in the models in a more detailed representation varying across EU member states. For MAGNET and CAPRI also cross-price elasticities are included in the modelling systems. In the calibration procedure elasticities are adapted so that constraints implied by economic theory are fulfilled, while keeping the deviation to the exogenous elasticities from the literature as small as possible. Applying elasticities for broad aggregated food products and country averages has the limitation that variation within product and population groups is lost in aggregation. Also, some of the elasticity sources have been published some years previous to the study at hand so that recent consumption trends could not be captured. As the same holds for most of the data underlying in the models, also the projected per capita consumption trends presented in Figure 2.2 may deviate if more recent information would show a persistent change from past trends. Furthermore, the applied elasticities are not validated for the imposed consumption shifts in the range analyzed in this study. We found similar tendencies of unenforceable high price shifts necessary to achieve a substantial consumption change on population level across the three economic models. We refrain from conducting a sensitivity analysis on our demand elasticities as this is only one, despite an important, element in modelling systems calibrated to very different settings than the pursued one. Instead, we want to stress the need for further research on how large-scale diet changes are achievable and in how far non-price interventions could affect demand elasticities and facilitate recommended consumption changes. Based on this information, future economic modelling projections can be better informed, more flexible and robust.

Table 2.4 EU demand elasticities for groups of food products targeted in the diet scenarios by model

EU demand elasticities	CAPRI	GLOBIOM	MAGNET
Underlying sources	Muhammad et al. (2011)	Muhammad et al. (2011), Alexandratos and Bruinsma (2012)	Aguiar et al. (2016)$^{+}$
Expenditure elasticities			
Vegetables & fruits	0.2519	-0.29	-0.001
Red & processed meat	0.4236	0.05	-0.001
Sugar	0.0004	0.12	-0.001
Own-price elasticities			
Vegetables & fruits	-0.2509	-0.18	-0.01 (-0.63)*
Red & processed meat	-0.3737	-0.28	-0.65
Sugar	-0.15	-0.26	-0.54 (-0.63)*

Note: Calibrated model elasticities are presented as weighted EU averages for the respective product groups $^{+}$Additional calibration of income elasticities is done in the MAGNET baseline to (1) improve response in demand pattern to strong income increases for current low-income regions by linking the income elasticities to real income per capita; (2) respect physical limitations on calorie consumption for current high-income regions by capping income elasticities at -0.001. Figures in the table are calibrated MAGNET values (weighted average using base year consumption values across EU28 regions for own price elasticities which vary by EU region). *Consumption of vegetables & fruits and sugar through processed food are also included in diet target, value in parentheses is the own price elasticity of processed food.

Due to the respective demand system specifications it was not possible for all models to enforce the envisaged diet changes via price interventions. In MAGNET the targeted increase for fruits and vegetables could not be achieved through a subsidy and a taste shifter has been employed instead. The technical reason is a low price elasticity for vegetables and fruits in the

EU region. These elasticities are estimated using an implicit, directly additive demand system (AIDADS) on GTAP data. While these appear low compared to other sources there is no immediate direction in which to change the elasticities without also considering the flow of vegetables and fruits through other food (which has a high elasticity of up to 0.75). In CAPRI the targeted reduction of sugar intake could not be reached as consumption quantities would have fallen below the minimum consumption levels, which are price- and income- independent elements of the generalized Leontief demand system as specified in the calibration procedure to ensure a diversified consumption bundle. For sugar demand, this parameter varies between 10 and 60 kg/cap/year (before deducting losses) for the EU member states in the underlying CAPRI calibration. This is very close to the simulated consumption, meaning that the largest part of sugar consumption is not responsive to prices in CAPRI, in line with the assumption that total sugar consumption is very inelastic. An additional reason for divergences results from the 'Armington (1969) approach' that considers domestic and foreign products to be of different qualities. In the baseline units are chosen such that consumption in quality corrected units is identical to physical units (tons). But in scenarios the quality corrected consumption in CAPRI differs from the physical consumption that is recalculated from the model solution. While the quality corrected consumption is very close to the envisaged target, after conversion into tons the results can deviate from the target. Integrating a parallel physical accounting into the model might be possible, but this will further increase the already long time needed to solve the model. The reported calories from MAGNET are derived from ex-post calculations accounting for two main channels through which primary products reach consumers (direct consumption and processed food). For all aggregated sectors, i.e. sectors where the MAGNET representation covers a wide variety of products, calorie contents per unit of product may vary considerably across countries. As a result, changes in trade flows may alter calorie content of purchased products, even if the total amount of product remains the same. As these calculations are ex-post we cannot target them in the scenarios, instead relying on a model variable measuring calorie contents without capturing trade-induced changes. While reporting ex-post numbers can result in discrepancies with targeted amounts, the ex-post calculations provide a more precise measure of calories by respecting the global balance in calories produced and demanded.

Accounted calorie values diverge systematically between the models. Daily calories available per capita on EU average range between 2441 kcal in GLOBIOM and 3776 kcal in CAPRI for BAU 2010 (see supplementary data, Appendix E). While further data improvements (and with it potential improvements in data consistency between models) are needed to validate and improve the representation of the consumption side in these large-scale economic models, the existing structures suffice for a comparable scenario implementation in relative terms.

As the representation of diets and nutrition is coarse in the large-scale economic models, we refer to the 955 FoodEx2 consumer products (including processed products with mixed ingredients) in the SHARP database for these indicators (Mertens et al. 2019). FoodEx2 is the second version of the standardized food classification and description system of the European Food Safety Authority (https://www.efsa.europa.eu/en/data/data-standardisation).

We refer to the nutrition score NRD9.3 to assess the impact on average nutrition quality for three EU member states calculated by MAGNET-SHARP. The improved scores arising from the food pattern (FP) scenario are close to the upper boundary of the range of nutritional differences observed within these populations. We calculate the normalized NRD9.3 based on the data provided by Mertens et al. (2018) and compare it to the average scores in the BAU and FP scenarios (Table 2.5).

Table 2.5 NRD9.3 comparison based on MAGNET-SHARP and observed population range

NRD9.3	Czech Republic	Denmark	France
BAU 2050	0.6	0.65	0.57
FP 2050	0.71	0.73	0.61
Observed population range, normalized*	0.46-0.58	0.53-0.67	Not available

Note: *The observed population range was calculated based on the NRD9.3 values for the 25th and the 75th percentile provided in Table 4 in Mertens et al. (2018). To retrieve normalized values between 0 and 1, we used the following formula: $NRD9.3_{normalized} = (NRD9.3 + 300)/1200$.

Food intake in SHARP excludes food waste and loss shares. There is no explicit tracking of food loss and waste in the economic models. Food loss and waste shares in the economic models are informed by the FAO Food Balance Sheets (http://www.fao.org/faostat/en/#data/FBSH) and partly by FAO (2011). For the MAGNET-SHARP mapping, food loss and waste shares are assumed to be constant over time.

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2.7.3 *C. Calorie reduction target calculation*

Overweight and obesity are the result of an imbalance between energy intake and energy use for maintenance, growth and physical activity. Working towards a population level policy which is rough by design, we average variations in age, weight, physical activity, and sex. We refer to an EU median age of 43 years in 2018 (Eurostat, 2019) and a mean height of 1.75 m for male and 1.65 m for female adults (Roser et al., 2020). For the four nutritional status groups ‘underweight’, ‘normal’, ‘pre-obese’ and ‘obese’ we make assumptions on the respective average body mass index (BMI), as we are missing information on the distribution of BMI within each group (see Table 2.6). Given the formula for calculating the BMI as dividing a person’s weight in kg by the square of the person’s height in m, we determine the corresponding weight for each nutritional status group for male and female. On this ground, we calculate the basal metabolic rate, the daily total energy expenditure of a person, using the equations provided by FAO (2004) and DAG (2014). To derive the daily calorie requirement for each group we assume a moderately active lifestyle with a physical activity level (PAL) of 1.75 on average and use a conversion from MJ to kcal of 1:239 (DAG, 2014).

The resulting calorie requirements are weighted with the population share of each nutritional status group in the EU in 2017 (Eurostat, 2020). The weighted average calorie requirement exceeds the requirement of the group with a 'normal' BMI by about 10%, so that we approximate this divergence as the relative calorie reduction target used for the model assessment.

Table 2.6 Calorie requirement for the EU population average by nutritional status and sex

Nutritional status	Avg. BMI* (kg/m²)	Weight (kg) male | female	Energy requ.+ (kcal/day) male | female	EU pop. share# (%) male | female	Energy requ. X EU pop. share male | female
underweight	18	57 | 49	2673 | 2177	2 | 5	43 | 109
normal	21	67 | 57	2864 | 2293	40 | 51	1134 | 1162
pre-obese	28	89 | 76	3246 | 2590	43 | 30	1409 | 772
obese	37	117 | 101	3848 | 3042	15 | 15	589 | 444
Weighted EU avg. energy requ. (kcal/day)					3174 | 2487
Excess energy intake on EU avg. relative to energy requ. of 'normal' (%)					11 | 8

Note: *As no information on BMI distribution within categories is available, we made assumptions of a potential average (avg.) BMI in these groups. +Energy requirements (requ.) are calculated based on the BMR formula in FAO (2004) for groups with 'underweight' and 'normal' nutritional status, and on the BMR formula in DAG (2014, p. 79) for groups with 'pre-obese' and 'obese' nutritional status. We assume a PAL of 1.75 on population (pop.) average. #Based on Eurostat (2020).

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2.7.4 *D. Meat consumption changes*

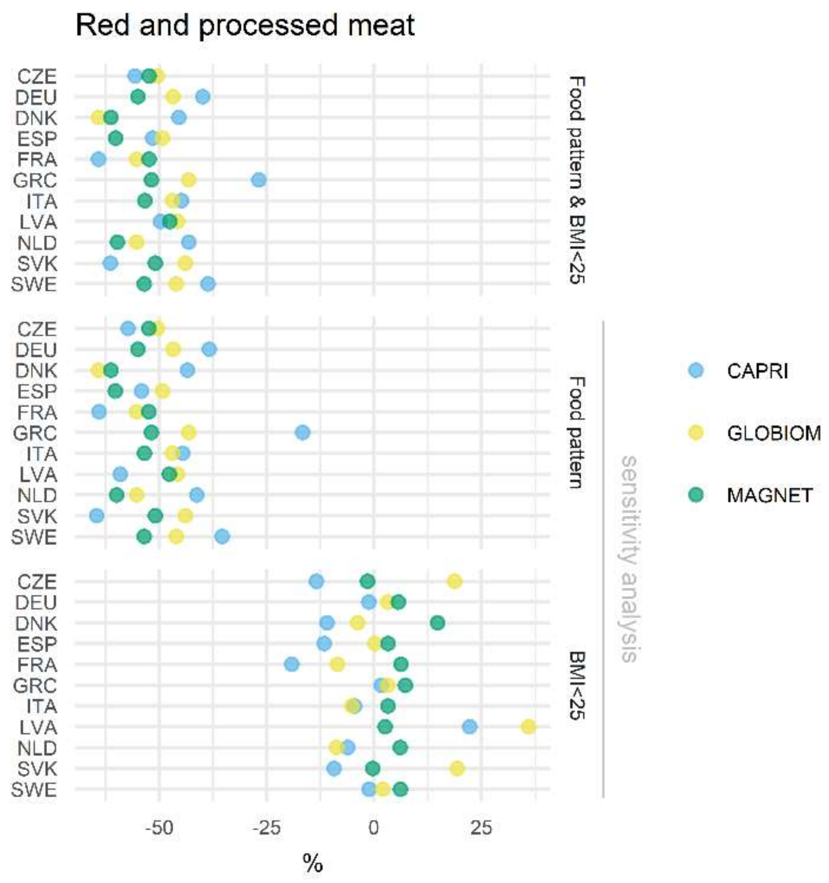

Figure 2.6 Percentage consumption changes for red and processed meat in EU member states relative to the business-as-usual scenario in 2010.
Note: The consumption shocks are imposed on EU average level and the models are not constrained to solve for an even distribution across EU member states. The displayed EU member states therefore may show a deviating pattern compared to the EU average change. Country names according to ISO 3166 Alpha-3 codes.

2.7.5 *E. Supplementary data description*

The description of the supplementary data provided with this article can be found in the online supplementary material of the published article under https://doi.org/10.1016/j.gfs.2020.100437.

2.7.6 *F. Supplementary data*

The supplementary data can be found in the online supplementary material of the published article under https://doi.org/10.1016/j.gfs.2020.100437.

Chapter 3
Competing for food waste – Policies' market feedbacks imply sustainability tradeoffs†

Abstract. Reducing food waste and reusing it as animal feed are often regarded promising solutions to enhance sustainability. Hitherto, food waste policy assessments rarely account for interdependencies between reduction and reuse interventions, and how their market - including trade - feedbacks influence sustainability outcomes. Here, we apply a global agricultural economic model to assess the impact of food system feedbacks on sustainability when EU consumer food waste is reduced or reused as pig feed. Our results show that food waste interventions easily result in sustainability tradeoffs. Halving food waste generates larger EU emission savings than its valorization as pig feed. EU savings remain below those expected when not considering market feedbacks, but additional emission savings are projected to arise abroad as consequence of shifting trade flows. When food waste is halved, decreasing food prices improve food access for consumers but reduce farmers' income. The use of food waste as pig feed is only economically competitive if this novel feed is comparably cheap but

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Credit: Catharina Latka: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. Alejandro Parodi: Writing – review & editing, Visualization. Ollie van Hal: Resources, Writing – review & editing. Thomas Heckelei: Writing – review & editing, Supervision. Adrian Leip: Writing – review & editing. Heinz-Peter Witzke: Methodology, Software, Resources. Hannah HE van Zanten: Conceptualization, Writing – review & editing, Supervision.

then it stimulates pig production and imports of protein feed with potentially unsustainable consequences. Food waste reduction limits the amount of food waste biomass available for valorization. This could create unintended competition for food waste biomass. Thus, clear food waste reduction and valorization targets are needed, potentially focusing valorization on inedible waste parts only. Policy-makers need to consider such interdependencies when designing food waste interventions.

Keywords: food waste, valorization, pig feed, greenhouse gas emissions, food system

3.1 Introduction

One of the declared EU policy goals is the reduction of food waste (European Commission, 2019). Halving consumer food waste by 2030 is manifested in UN SDG target 12.3 (UN, 2015). Besides reduction, EU policies aim to valorize food waste biomass to decrease the need for resource inputs and increase circularity in the economy (European Commission, 2020a, 2020b, 2019).

Reducing and valorizing food waste is foremost argued to be of environmental, economic and social benefit (Kummu et al., 2012; Lopez Barrera and Hertel, 2021). However, in an interconnected food system, the benefits for some may turn out as costs for others (Rutten, 2013). For instance, valorizing food waste as animal feed can avoid feed-food competition and reduce the use of natural resources (van Zanten et al., 2018). However, declining food and feed demand as consequence of food waste interventions might lower agricultural production levels and thus reduce producers' income and economic growth (Campoy-Muñoz et al., 2017; Kuiper and Cui, 2020; Philippidis et al., 2019). Also, resulting implications for food availability and food security depend on the actual implementation of food waste reduction interventions and how the markets adjust in consequence. Thus, assessments of food waste interventions need to account for potential consequences across sustainability dimensions to capture occurring tradeoffs at food system level so that these end up being considered in actual policy design.

Existing studies rarely account for market and trade feedbacks of food waste interventions (Section 3.2). Some food waste assessments imply that embedded environmental impacts are reduced proportionally to the prevented food waste as they implicitly assume that this food is not produced anymore (Birney et al., 2017; Usubiaga et al., 2018). This approach, however, neglects trade, market, and rebound effects that influence the extent to which and where environmental improvements actually occur (Kuiper and Cui, 2020; Lopez Barrera and Hertel, 2021; Salemdeeb et al., 2017a). Furthermore, the simultaneous implementation of different food waste policies may cause conflicts as preventing food waste reduces the potentially available biomass for valorization. Although the hierarchical ordering of food waste measures favors prevention (Papargyropoulou et al., 2014), in political reality, several policies are often implemented at the same time. Assessments must therefore assess interventions jointly and at food system level, including market feedbacks, for effective policy coherence.

With this study we add to the literature by analyzing the effects of two EU consumer food waste interventions on food consumption, production, trade flows, and environmental impacts (i.e., emissions, nitrogen surpluses, agricultural land use change) using a global partial equilibrium (PE) economic model for the agricultural sector. The first intervention results in a 50% reduction of avoidable consumer food waste (FWcut). The second intervention is based on the valorization of plant-based consumer food waste as pig feed (FWfeed). Both interventions are assessed separately and in combination (FWcombi). Our analysis shows that reducing avoidable consumer food waste can improve food access as market feedbacks lower prices. Producers on the other hand need to cope with a declining demand for their products. Our results emphasize the environmental benefits of an EU-wide reduction in avoidable consumer food waste and where these may occur, whereas those related to valorizing food waste as animal feed are smaller and the establishment of a valorization system might create future demand for food waste and incentives for increased pork production and consumption and imports of protein feeds.

3.2 Literature review

A growing number of scientific research assesses food waste in terms of occurring amount (e.g., Caldeira et al., 2021), how it is linked to prosperity (e.g., Lopez Barrera and Hertel, 2021; Verma et al., 2020), its nutritious quality, the embedded environmental impact (e.g., Chen et al., 2020), economic costs (Muth et al., 2019) or the number of people who could supposedly be fed (e.g., Garcia-Herrero et al., 2018; Kummu et al., 2012). Many of these studies assess food losses and waste along the supply chain in one combined approach (e.g., Caldeira et al., 2019). However, causes and reduction implications differ depending on the stage of the food system at which the food loss or waste occurs (Cattaneo et al., 2020). Here, we focus on food waste at the consumption stage.

Out of sustainability reasons, food waste prevention and valorization (for human consumption (Makov et al., 2020) or as animal feed (Teigiserova et al., 2020)) are regarded the most preferable options (Papargyropoulou et al., 2014). The following literature review discusses their food system-wide sustainability implications and that these may go beyond the impacts embedded in the wasted food.

3.2.1 *Food waste reduction impacts*

Household surplus food is caused by low food prices (Rutten, 2013), edibility, or food safety concerns after the labelled expiration date, lack of awareness or knowledge about food waste related issues, cooking and shopping routines as well as oversized food packages (Schanes et al., 2018). Awareness and education programs can inform about the amount and impacts related to food waste, the correct interpretation of date markings, and improved planning (Muth et al., 2019; Schanes et al., 2018).

Numerous studies address the links between food waste reduction, food security and environmental sustainability (Shafiee-Jood and Cai, 2016). Usubiaga et al. (2018) show that a 50% reduction in EU consumer food waste would have lowered the environmental footprint in 2020 by up to 7% compared to 2011. Makov et al. (2020) find net emission savings if food waste is reduced by peer-to-peer sharing. The impacts estimated in these analyses relate to those embedded in the previously wasted food which is implicitly assumed to not be produced anymore as consequence of the food waste reduction.

Some studies refer to the potential cost savings for consumers (e.g. Birney et al., 2017) or for the economy (Campoy-Muñoz et al., 2017; De Laurentiis et al., 2020) when food waste is reduced. However, if food waste reduction lowers production, processing, retail, and treatment of these products, this could have negative implications for revenues and employment in the food system, at least in the short term. Despite those temporary potential economic pitfalls, reducing food waste is also called for in the degrowth debate (Hoehn et al., 2021) which challenges the logic of the contemporary economic system.

Food loss and waste reduction is furthermore claimed to improve food security (Vilariño et al., 2017). Kummu et al. (2017) show the potential for increased food availability resulting from food waste reduction. However, the question arises, why producers should continue to produce food if demand (e.g., for the wasted food) declines (Friman and Hyytiä, 2022). Preventing retail food waste by food donations could improve food security of low-income households, whereas improved planning could reduce the food available to donations (Galli et al., 2019). Thus, food system implications would largely depend on the type of interventions that cause the food waste reduction (Bajželj et al., 2020).

Life-cycle and cost-benefit analyses do not account for market adjustments resulting from food waste reduction (Muth et al., 2019). Demand may drop and the reallocation of money previously spent on food affects resulting impacts on the environment, food security and welfare (Rutten, 2013). Costs and tradeoffs are involved in reducing food waste and thus there might be an optimal, non-zero level of societally desirable food waste (Ellison et al., 2019; Rutten, 2013). Economic equilibrium models are especially suited for comprehensive food waste assessments, as they account for food system feedbacks and are able to assess impacts of policies in ex-ante simulations.

Britz et al. (2014) apply an EU-level computable general equilibrium (CGE) model and find that consumers benefit from household food waste reduction as long as costs involved are low and the agricultural sector gains from a demand shift toward more expensive products. In contrast, Campoy-Muñoz et al. (2017) assess a reduction of avoidable household food waste and find reductions in GDP and employment across EU countries using linear CGE models. Philippidis et al. (2019) simulate a 50% reduction in household food waste across the EU with the CGE model MAGNET. In consequence, real GDP and agricultural employment decrease, whereas the agri-food EU trade balance slightly increases.

Okawa (2015) models the reduction of food waste for selected countries revealing large consumer savings in, and export increases from the reducing countries based on a PE model. Thus, food waste reductions by selected countries imply changes in international trade flows. Greater trade integration enhances food security improvements that result from food waste reduction by facilitating food access to vulnerable groups according to a global PE assessment by Lopez Barrera and Hertel (2021).

Net food consumers and producers tend to be affected in opposite ways. Rosegrant et al. (2018) reveal that investments to reduce post-harvest losses can result in reduced food prices and improved access for low-income food buyers, whereas producer surpluses are reduced. Kuiper and Cui (2020) show that a food loss reduction at the production and processing stage only in trading partner countries can harm the food security of domestic agricultural households through import substitution with MAGNET.

Philippidis et al. (2019) estimate that halving EU consumer food waste can reduce land use in the EU by 0.5% and even more abroad. They find agricultural emission and irrigation water savings of up to 3.5% and 0.6%, respectively, in the EU. Changes in trade flows thus influence where environmental pollution can be reduced and how production and food security in these regions may be affected.

3.2.2 *Food waste valorization impacts*

Historically it was common to valorize food waste arising at the consumption stage as animal feed and contemporarily food waste treatment technologies exist that enable converting food waste to safe and nutritious animal feed (e.g., Dou et al., 2018; Qi et al., 2021).

Valorizing food waste as animal feed is found to be cost-effective for livestock producers (Dou et al., 2018), who may save costs for purchasing conventional feed. However, additional costs may occur related to handling the recycled 'food waste feed' (FWF), potentially required licenses to guarantee food safety, and changes in rearing time or selling price of the animals (Spinelli and Corso, 2000).

Feeding livestock only on grassland, food waste and byproducts is found to not compromise human food energy supply (Schader et al., 2015) and to deliver sufficient animal protein according to dietary recommendations (van Hal et al., 2019; van Zanten et al., 2016). To improve the valorization of food waste, mandatory separate collection of food waste would need to be introduced and collection logistics to be facilitated (Schanes et al., 2018). Moreover, establishing a standardized food waste treatment system could ensure the feed's safety (zu Ermgassen et al., 2016).

Food waste treatment processes for the conversion to animal feed are associated with lower emissions than other waste management options (Dou et al., 2018; Salemdeeb et al., 2017b). By reducing the demand for feed crops additional environmental savings can occur as consequence of valorizing food waste as animal feed (Dou et al., 2018). This could also reduce import dependencies for these products (Chaboud and Daviron, 2017).

Environmental advantages are found to occur if livestock is fed only on grassland, food waste and byproducts (Schader et al., 2015; van Zanten et al., 2016). Röös et al. (2017) show that feeding livestock on such "ecological leftovers" can reduce land use and greenhouse gas emissions (GHGE) of domestic diets by about one third even under a 50% reduction in food waste. Globally, the land competition between food and feed production could be minimized when feeding livestock only on leftovers (van Zanten et al., 2018).

Hitherto, a food waste valorization assessment accounting for economic market feedbacks is missing. Overall, there remains a need to better understand the socioeconomic, environmental and indirect effects of food waste reduction and valorization under consideration of market and trade feedbacks, and to identify synergies and tradeoffs between food waste reduction strategies (Goossens et al., 2019). With this study, we contribute to existing research by jointly assessing food waste reduction and valorization and by investigating sustainability tradeoffs at food system level.

3.3 Methodology

To contribute to the aforementioned research gaps, we apply an established agricultural economic PE model that is able to capture the global food system including economic market feedbacks that are hard to capture with LCA approaches. We focus on retail and household food waste, holding the largest waste share (51%) along the EU food value chain (Caldeira et al., 2019), and quantify food waste as the difference between average national level food availability and intake distinguishing avoidable and unavoidable waste shares for broad food groups (Vanham et al., 2015). Economic, social and environmental impacts of the scenarios are assessed relative to the setting in our Baseline for 2030 (Section 3.2, 3.6). In a sensitivity analysis, we highlight the role of FWF prices for a successful valorization policy. Further details on the methodology are provided in the following subsections.

3.3.1 *Model description*

We apply the Common Agricultural Policy Regionalized Impact modelling system (CAPRI) (Britz and Witzke, 2014). It is built for comparative static policy and market impact assessments covering global and, for EU member states, also regional scale. CAPRI contains a spatial, non-stochastic global multi-commodity model. It is defined by a system of behavioral equations representing profit or utility maximizing economic agents. Consumer demand is based on generalized Leontief expenditure functions (Ryan and Wales, 1999). Resulting indirect utility functions depend on prices and increase in income. Underlying demand elasticities are based on Muhammad et al. (2011) and adjusted in the calibration to comply with microeconomic theory (Britz and Witzke, 2014). The consumption side is represented by an average national consumer. Trade flows are modelled in a two-stage demand system which differentiates domestic sales and imports (Armington, 1969). This global model is linked to regional programming models for EU regions maximizing farm income subject to market prices. The availability of land, compliance with agricultural policies, and the interplay of soil nutrient needs, feed requirements in line with animal nutrition, and livestock production serve as boundary conditions for EU agricultural production in the modelling system. Environmental indicators (Section 3.6) are calculated for the scenario-specific agricultural production settings (Britz and Witzke, 2014; Leip et al., 2015). Further details on the modelling setup are provided in Appendix C.

3.3.2 *Consumer food waste representation in the Baseline*

Food group specific consumer food waste shares in our CAPRI Baseline are informed by existing research for European countries (Vanham et al., 2015) and other world regions (FAO, 2011). The food group specific waste shares from FAO (2011) only consider edible waste and report meat related waste on a carcass weight basis (Gustavsson et al., 2013). Thus, we recalculate these waste shares given the information regarding avoidable and unavoidable waste in Vanham et al. (2015). Consequentially, we end up with a set of food group and world region specific waste shares that differentiate avoidable and unavoidable waste parts.

We interpret avoidable food waste as food that is or was edible for humans, in contrast to inedible food parts like e.g., some fruit kernels, which we refer to as unavoidable food waste. We acknowledge prevailing differences in perceptions of edibility (FLW Protocol, 2016), but cannot account for this given the level of product aggregation in the model. Consumer food waste captures retail, services and household food waste, which is not distinguished in CAPRI. Lastly, we consider recent evidence by Verma et al. (2020) who reveal considerable underestimation of consumer food waste in previous research. Therefore, we align wasted calories to represent the relation to affluence estimated by Verma et al. (2020) while keeping the contribution of food groups and the distribution of avoidable versus unavoidable waste as previously outlined (for implementation details refer to Appendix C). Historical food demand in CAPRI is informed by available food per capita provided by Eurostat and FAO food balance sheets which includes waste at the consumer stage (FAO, 2001). We convert available food quantities to calories and apply the previously outlined steps to distinguish waste from intake shares. We are aware of the roughness of this approach considering likely if not obvious differences in calorie contents for avoidable and unavoidable food waste. Food waste collection and treatment are yet beyond the boundaries of the modelling system (Figure 3.6 in Appendix C).

3.3.3 *FWcut scenario – reducing avoidable consumer food waste*

In our food waste scenarios we test two potential EU policies. First, we simulate a successful food waste reduction campaign (e.g., an EU wide information campaign about food waste impacts) having resulted in a 50% reduction of avoidable consumer food waste (FWcut). We implement this as a preference shift, i.e. halving the purchases of previously wasted but edible food in the Baseline. In the implementation we ensure that food intake does not directly increase as a means of reducing waste, but can only be affected indirectly via market feedbacks. Since the reduction of food waste is implemented as an exogenous shock on the Baseline food waste share, market feedbacks that reduce food prices can partly counteract the reduction of food waste quantities.

3.3.4 *FWfeed scenario – valorizing plant-based food waste as pig feed*

With our second policy scenario, we explore the impact of a change in EU legislation toward allowing and promoting plant-based consumer food waste to be used as pig feed (FWfeed). The available biomass is linked to the food waste arising at the consumption stage within the respective EU member state in the current simulation. Food-specific energy and protein contents available to pig nutrition are aligned to those underlying in van Hal et al. (2019) (Table 3.2 in Appendix C). In the whole EU, plant-based food waste biomass sums up to 96.000 tons fresh matter in 2030 in this scenario, replacing between 5% and 100% of net energy and between 3% and 100%

of crude protein required for pig fattening across EU member states depending on a country's food waste composition and pig feed demand in our Baseline. Current pig production systems in the EU do not rely on the use of food waste as feed. Given the novelty of this potential feed product, historic market data are missing for model calibration and simulation procedures. Instead, we assume that political incentives to valorize occurring consumer food waste lead to a complete utilization of available FWF within a country by pig production activities at no input cost for the farmer. In our simplified scenario assessment, FWF is not subject to inter-country trade.

In order to disentangle synergies and tradeoffs, we furthermore assess the two presented policies in combination (FWcombi). The halved available consumer food waste reduces the plant-based food waste biomass available as pig feed. Remaining consumer food waste quantities that are not directed to pig feed are assumed to be handled by existing treatment facilities as in the Baseline, which are outside the model boundaries.

3.3.5 *Sensitivity analysis on FWF costs and available quantities*

We do not account for governmental or technical implementation costs at farm stage related to FWF in the FWfeed scenario. However, we acknowledge FWF costs to be a relevant and uncertain variable in this assessment. Therefore, we explore different levels of arising costs to the farmers in a sensitivity analysis (FWfeedSens). In Japan and South-Korea FWF is delivered at 40–60% of the cost of conventional feed based on commercial blends (zu Ermgassen et al., 2016). Feed costs can be lowered when using left over feed in broiler diets (Cho et al., 2004). Producers tend to be willing to pay only a small price for processed food waste as alternative pig feed due to lower feed conversion ratios than for conventional feed (Spinelli and Corso, 2000). While processing, control and transportation of FWF are not explicitly captured in our model, related costs arising at these value chain steps are implicitly captured in the FWF prices farmers may be facing.

In our FWfeed and FWcombi scenarios we use all potentially available plant-based food waste in a country as feed, but based on real-life examples from Japan and South Korea a more realistic scenario would be to only use

35–45% of the food waste as feed (Ng et al., 2017; zu Ermgassen et al., 2016). In our sensitivity analysis, we therefore also test varying available FWF amounts in combination with different prices. The maximum FWF price we assume equals the average producer price for conventional feed in the 2030 Baseline for each EU member state and is imposed on a net energy basis. Of this maximum (100%) we test further price levels in quantile steps. The maximum FWF amount is all plant-based food waste biomass as it is available in the FWfeed scenario.

3.3.6 *Food system feedbacks*

Food system feedbacks resulting from the imposed food waste policy changes are assessed with respect to economic, social and environmental impacts. Economic feedbacks include those on food and feed purchases, production activities, trade, and related prices. It should be noted that consumer prices are generally higher than producer prices as these subsume additional markups along the supply chain. Producers' income is subject to their production costs, demand for their products, and prices they retrieve from selling on the markets, plus possible revenues from other potential income streams (e. g., tourism, , direct marketing to consumers). Changing prices are of social relevance since they affect the accessibility of food. In addition to food availability (i.e., market food supply in the model), we capture impacts on two food security dimensions. Agricultural emissions to the atmosphere, nitrogen surpluses and agricultural land use changes are the environmental impacts investigated in this study. These impacts are calculated for the projected production activity changes related to the specific scenarios by referring to emission inventories and nutrient balances based on IPCC (2006) and Leip et al. (2011). For comparison purposes, we use the product-based emission coefficients in CAPRI (Weiss and Leip, 2012) to calculate the emission reduction potential in our food waste reduction scenario that could be expected when market feedbacks are not considered. Figure 3.1 provides an overview of the food waste representation, scenario design, and indicators used in this study.

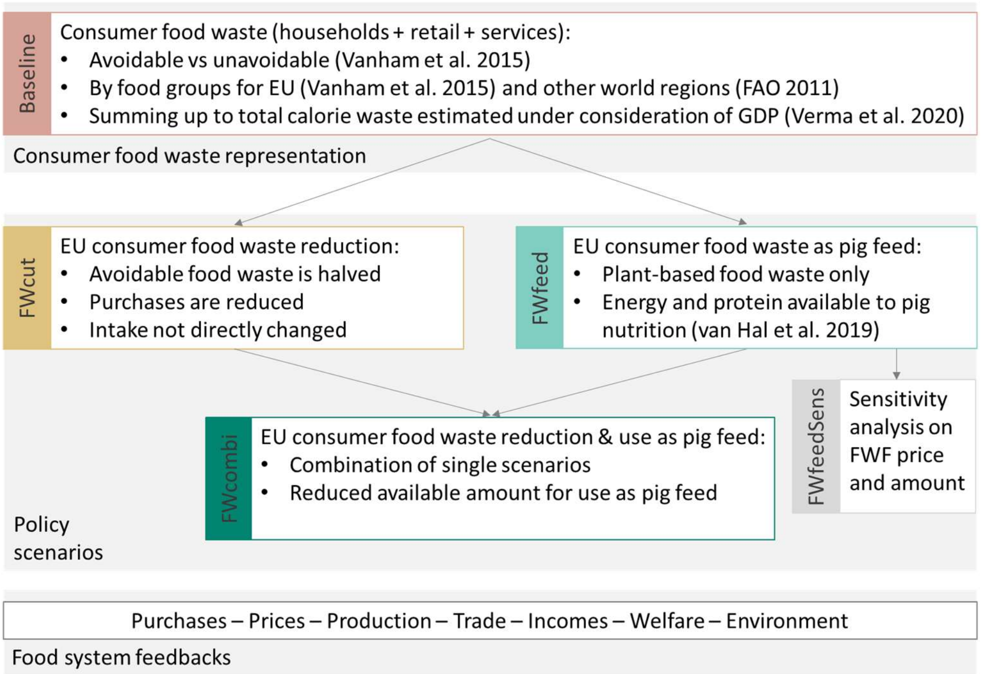

Figure 3.1 Methodological overview summarizing the consumer food waste representation in the Baseline, policy scenarios, and food system feedbacks.Note: FWF = food waste feed.

3.4 Results

3.4.1 *Effects of food waste interventions on EU markets and trade flows*

In the Baseline 2030 results food waste varies between 7% and 38% of available food calories per capita and day on EU country average, the majority being avoidable waste (Figure 3.2, Appendix A, B). While 38% seems to be a high loss rate, it must be considered that this also contains food waste in the retail and service sectors (i.e., catering, restaurants). Resulting waste shares are in line with up to 43% across member states and with 27% on EU average found in similar and related research (Lopez Barrera and Hertel, 2021; Verma et al., 2020).

In the FWcut scenario, avoidable waste is halved which results in a demand reduction for human consumption across food groups (Figure 3.3a). As consequence, food prices decrease slightly resulting in an endogenous,

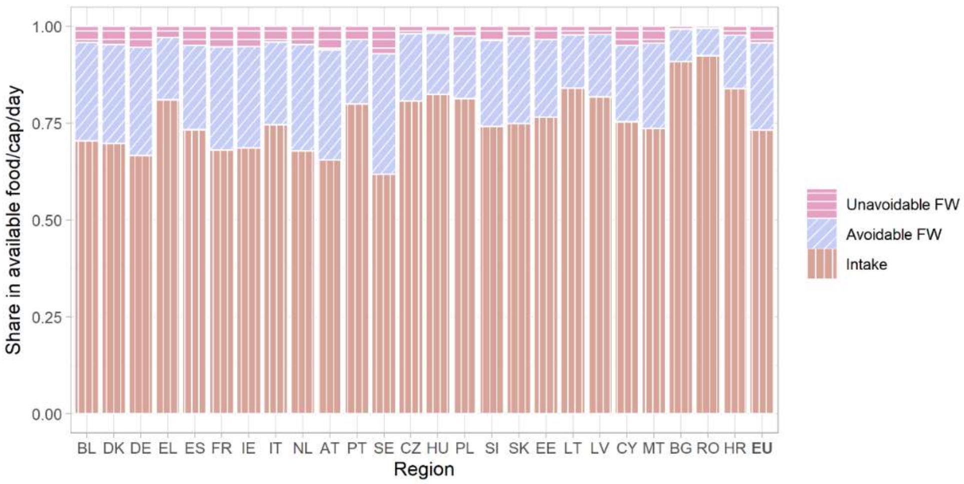

Figure 3.2 Consumer food calorie intake, avoidable and unavoidable waste share in Baseline in 2030. Note: X-axis shows the ISO-Alpha-2 region codes, except for BL = Belgium and Luxembourg, EU = European Union. FW= Food waste.

partial reversal of the exogenous initial decline in demand (Figure 3.3c, Appendix C). This rebound effect counteracts the behavioral change in food waste reduction. On EU average, falling producer prices (Figure 3.3d) lead to a food production decline, but the reduction is less strong than the reduction of food demand. EU production of fruits, vegetables, meat, and cereals declines by 4–5% (Figure 3.3b) compared to a 9–17% reduction in respective consumer demand, and potato, pulses, roots and tubers production is reduced by 17% compared to a 31% food demand reduction. The production reaction is smaller for two reasons. First, additional demand arises from feed and industrial sectors as consequence of the price decline. Second, a generally high share in production for export, increasing exports and reduced imports ease the impact on EU agricultural producers (Figure 3.3g,h, Appendix A).

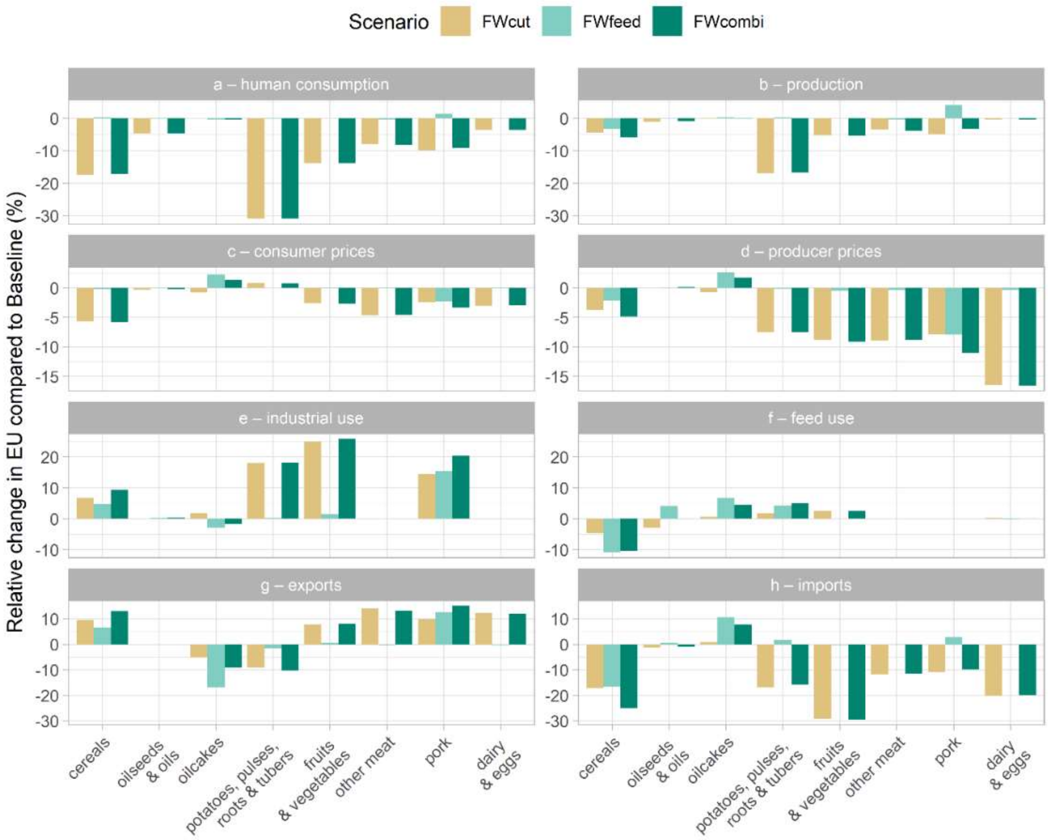

Figure 3.3 Price and market feedbacks by scenario, variable and product in EU 2030 relative to Baseline.

In the FWfeed scenario all plant-based food waste is considered available to pig production as alternative feed. FWF is a rather low-protein, high-energy feed alternative given the food waste mix that is endogenous to our model projections and the assumptions on food waste nutrients available for pig diets (Section 3.3). Valorizing consumer food waste as pig feed has a small impact on EU consumer prices and food demand (Figure 3.3a,c). However, EU producer prices for pork meat (-8%), cereals (-4%), and oilcakes (+3%) are affected noticeably (Figure 3.3d). Cereal production is reduced (-3%) while pork production increases (+4%) as consequence of the assumed usage of the FWF substitute at no cost for pig producers in this scenario (Figure 3.3b,f). For EU trade flows this implies import reductions especially in cereals (-17%) and import increases of protein rich oilcake products (+11%). EU exports adjust complementarily, with a decline in oilcakes (-17%) and an increase in pork (+12%) and cereals (+7%) (Figure 3.3g,h, Appendix A).

In the FWcombi scenario, production impacts for cereals add up (-6%) while they counteract for pork (-3.3%) (Figure 3b, Appendix A). Oilcake imports for animal feed persist, though to a lesser extent than in the FWfeed scenario due to the reduced amount of available food waste biomass.

3.4.2 *Price effects on food intake and farmers' income*

Food intake is not directly targeted in the FWcut scenario because the food waste reduction is implemented as a corresponding drop of purchases by EU consumers. However, price and production changes can indirectly affect food intake in and outside the EU. Induced by market price feedbacks, we find that declining food prices increase the EU average intake of fruits and vegetables (+10%), meat (+2%) and dairy products (+3%). While the increase in vegetable intake likely contributes to an improved nutrition, the increase in meat rather conflicts with nutrition recommendations for the EU average (Mertens et al., 2018). In comparison, when valorizing food waste as pig feed (FWfeed), food intake changes marginally in the EU with at most a 1% increase in EU pork intake. Also in this scenario, aggregated meat intake increases slightly despite a small decrease in the consumption of all non-pork meats.

Relative to the 2030 Baseline, in the FWcut scenario farmers are negatively affected across production activities as consequence of the drop in demand. In the FWfeed scenario pig fattening costs decline on EU average by 7.2% with a range from 0.2% to 86.3% across member states. Combining both scenarios (FWcombi) offsets the cost reduction for pig fatteners partly as considerably less food waste biomass is available after halving avoidable food waste.

The reuse of food waste in pig production in the FWfeed scenario has ambiguous impacts on producers of conventional feed, because the food waste biomass supplies pigs well with energy but is comparably low in protein. In consequence, EU cereal producers are negatively affected, whereas oilcake production slightly increases (+0.4%), and oilcake exports strongly decline (-9.8%).

Trade reactions impact food production and prices outside the EU, but the model does not suggest strong dietary changes in the rest of the world for the FWcut scenario in line with globally moderate market shares of the EU. Nevertheless, net production of some foods decreases non-negligibly in some trading partner countries (e.g., fruit and vegetable production in Oceania and Latin America (-3%), pork production in Africa (-6%) as a result of the strong drop in EU import demand.

In the FWfeed scenario, food intake abroad also changes marginally. Agricultural production in other countries is mainly affected in two sectors. Most dominantly, pork production declines in African countries by about 5% on average as consequence of the increased competitiveness of EU producers. Also, cereal producers outside the EU are negatively affected (up to -2%). However, EU dependency on oilcake imports from non-EU countries increases as reaction to the increased protein feed demand. The FWcombi scenario implies that specifically imports of cereals, fruits, and vegetables fall.

3.4.3 *Emission savings in and outside the EU*

EU agricultural GHGE decrease by about 4% (-16 Mio t CO2eq) when halving avoidable consumer food waste (FWcut) compared to the Baseline scenario (Figure 3.4). The valorization of food waste (FWfeed) reduces agricultural GHGE as well, however, to a considerably smaller extent (-0.2%).

The underlying member state emission changes reveal a similar trend overall. The absolute reduction varies and depends on population size, food purchase composition and food waste quantities (which we made dependent on GDP development). For some EU countries an increase in GHGE occurs as reaction to the usage of food waste in pig feed when additional emissions from increased livestock production exceed emission savings related to reduced feed inputs in the FWfeed scenario (this is the case especially for

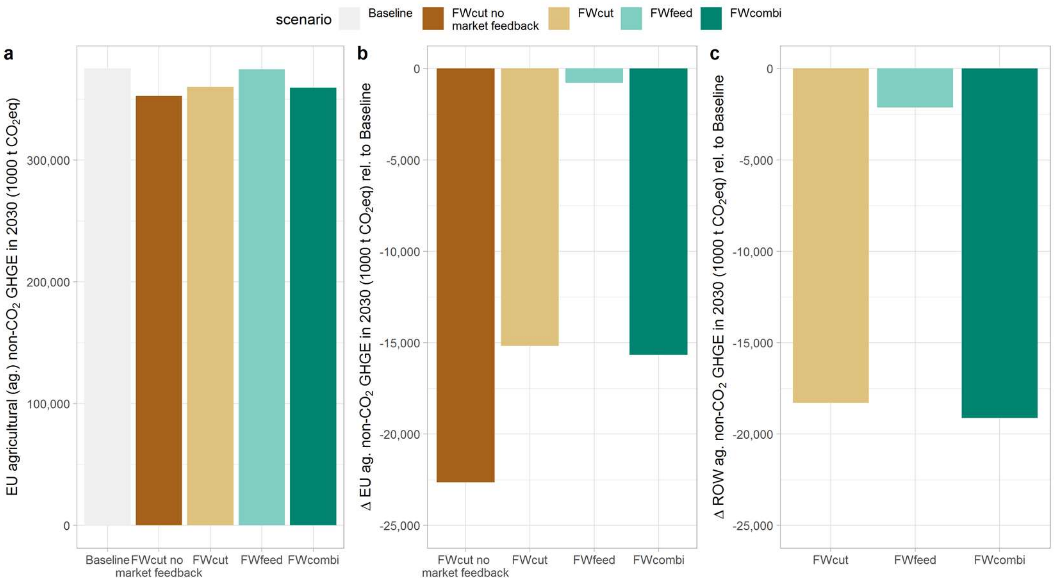

Figure 3.4 Agricultural greenhouse gas emissions (GHGE) and emission changes relative to Baseline in 2030 for the EU and rest of the world (ROW).

Malta (+10%), Italy (+3%), and Czechia (+2%)). Combining both interventions (FWcombi) results in emission savings for all member states.

In various existing, often LCA-based studies on food waste reduction, it is, implicitly or explicitly, assumed that the reduction of food waste results in the respective reduction of the embedded environmental impact. This assumption however neglects potential market feedbacks from price changes and implications in other sectors, industries, and for trade. In Figure 3.4 we present this as EU emission reduction related to halving avoidable food waste when considering "no market feedback". It is based on the simplified assumption that emissions are reduced proportionally to the reduced domestic demand in the FWcut scenario without considering price or trade reactions. Next to this, the actual GHGE reductions from our simulations are presented for the EU and the rest of the world. EU emission changes from the simplified expectation exceed those in the actual scenario results, because market and trade changes prevent EU agricultural production from declining as much as EU food demand. Since agricultural production declines in non-EU regions, additional emission savings occur abroad. Different emission intensities in agricultural production across the globe imply that non-EU emission savings might even exceed those achieved within the EU, so that global emission savings from reducing food waste may be even larger than a proportional calculation ignoring market feedbacks suggests (Figure 3.4).

3.4.4 *Other environmental implications*

Reducing avoidable food waste by 50% in the EU (FWcut) reduces nitrogen surpluses per hectare (-3%) related to EU agricultural production. In contrast, reusing food waste as pig feed (FWfeed) reveals a net zero change in nitrogen surpluses resulting from reduced mineral fertilizer application and an increase in manure application in the EU. The combined intervention set-up (FWcombi) leads to nitrogen surplus reductions comparable to those in the FWcut scenario.

Agricultural land use in the EU is reduced by less than 1% (-1.1 mio ha) in the FWcut scenario. This area mainly transforms to fallow land (+2%, +0.8 mio ha) showing that the drop in food demand makes agricultural production unprofitable in some areas. Valorizing food waste as pig feed (FWfeed) shows even smaller effects on EU land use patterns with cropland area being reduced by about 0.4% (-0.4 mio ha). However, the share of crop area devoted to cereal production declines in some member states to the benefit of oilseed production and fallow land.

3.4.5 *Sensitivity analysis – Food waste as marketed pig feed*

Production costs related to the use of food waste as pig feed have so far been neglected and the complete use of hypothetically available plant-based food waste has been assumed in the FWfeed and FWcombi scenarios. To assess the sensitivity of our findings, we vary the FWF price and the food waste biomass available for pig feed. Our sensitivity analysis shows that, as long as the price for FWF is low, overall production costs related to pig fattening decrease with an increasing amount of available plant-based food waste used as pig feed (white numbers in Figure 3.5a). However, with a price for FWF above 50% of the price for conventional feed, production costs even exceed the costs in the Baseline scenario (black numbers in Figure 3.5a).

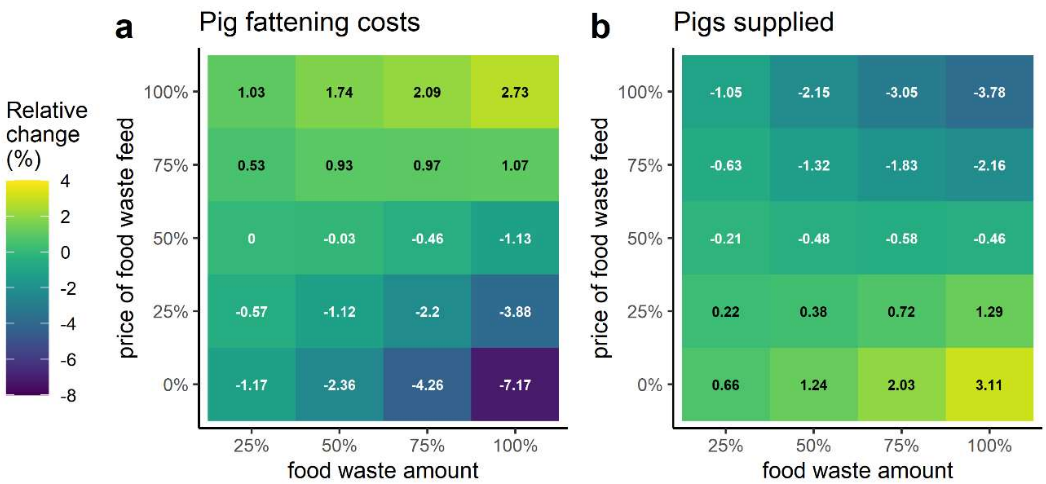

Figure 3.5 Percentage change in total production costs for (a) and the number of supplied animals by (b) EU pig fattening on average compared to Baseline in 2030. Note: food waste amount as share in total available plant-based consumer waste quantity, price of food waste feed as share of conventional feed price.

In our scenarios, EU pig farmers have no choice but to use all available FWF since historical market data is not available to simulate real market effects. In this setting, a FWF price at the level of average conventional feed would reduce pig production by 1–4% depending on the available amount of FWF (Figure 3.5b). Due to the low protein content of FWF, additional protein feed is required to achieve a balanced pig diet (i.e., up to 15% increase in protein-rich feed use for pig fattening in sensitivity scenarios). In case of political desirability to reuse food waste as pig feed, the sensitivity analysis implies the need for a low, maybe even subsidized price of this alternative feed to be competitive vis-à-vis conventional feed, unless a price premium is expected to be gained on the market for “circular pork meat”.

If the costs related to feeding FWF are low (e.g., due to subsidies or overabundance) and a sufficient amount of plant-based food waste biomass is available, an overall increase in EU pig production compared to the baseline is expected. This could stimulate an increase in EU pork consumption (by 4 kcal/cap/day on EU average) as well as in EU pork exports.

EU emission savings increase with a higher FWF price given the implied reduction in EU pig production. At global level though, agricultural emission savings are positively related to agricultural production staying within the EU due to its assumed higher emission efficiencies. However, additional emissions from transportation and deforestation related to imported protein feed, that are not captured in our results, could counteract those savings. Even if emissions are reduced in all food waste scenarios compared to the Baseline, it might be questionable whether a policy-induced increase in EU pig production is desirable in the light of pursued sustainability targets (Sandström et al., 2018). Thus, the actual design of policies steering the reuse of food waste, interrelating policies (e.g., regulations on feed imports (Karlsson et al., 2021)), costs for farmers, and the available food waste biomass will influence the overall sustainability outcome of such interventions.

3.5 Discussion and conclusions

3.5.1 *Interdependencies between food waste reduction and valorization as pig feed*

In line with previous literature (e.g., Okawa, 2015), our results show that reducing consumer food waste by better planned purchases improves food affordability on average. Food waste valorization is a smaller shock to the food system. Net-reduced purchases in both scenarios though imply losses for (some) food producers in the EU and via trade effects abroad as also discussed in Kuiper and Cui (2020) for food loss reduction. In the FWfeed scenario, production and trade impacts are focused on the meat and animal feed sector.

We find that EU agricultural GHGE can be reduced by 4% when halving avoidable consumer food waste. This is in line with Philippidis et al. (2019) who project a reduction of 3.5% in a comparable analysis. If we combine both interventions, the additional savings compared to the FWcut scenario are only minor and the already much smaller contribution of the reuse as pig feed further shrinks because less biomass is available due to the consumer food waste reduction.

This shows that the interdependencies between food waste interventions – and whether these may compete for food waste biomass – depend on the order of their implementation (Papargyropoulou et al., 2014) and the actual interpretation of policy targets. It is an ongoing debate whether valorizing surplus food as animal feed contributes to food waste reduction (e.g., Goossens et al., 2019). The UN SDG 12.3 target to halve food waste refers to uneaten food that "goes to destinations other than animal feed or bio-based materials/ biochemical processing" (Champions 12.3, 2017). Since also the reduction of inedible food parts is envisaged (Champions 12.3, 2017), making increasingly use of valorization options like reuse as animal feed may be necessary to reach this goal.

Some researchers state that only inedible, unavoidable fractions should be valorized (Corrado et al., 2020; Van Zanten et al., 2019). Given that large parts of the arising food waste at the consumption stage are counted as avoidable, it remains questionable whether unavoidable parts represent a sufficient amount for setting up a competitive valorization system. The assessment of our FWfeed scenario reveals that valorizing even all available plant-based food waste biomass is limitedly competitive and environmental benefits are small compared to halving all avoidable food waste occurring at consumption stage. Our valorization scenario is only limitedly comparable to existing studies. We focus on integrating available food waste in the pig diet whereas existing analyses (Röös et al., 2017; Schader et al., 2015) assess scenarios in which animals are only fed by valorized food waste and other ecological leftovers. These studies implicitly restrict animal production and thus result in stronger environmental benefits than in our analysis of a somewhat more likely setting.

3.5.2 *Potential non-accounted effects*

According to our scenario results, halving avoidable EU consumer food waste decreases agricultural production to a considerable extent abroad, whereas the valorization of food waste as animal feed increases demand for protein-rich feeds such as soya to balance pig dietary requirements. Environmental impacts from land conversion have not fully been accounted in this assessment such as potential deforestation related to increased feed demand (Escobar et al., 2020; Karlsson et al., 2021). Emission savings from the valorization as animal feed could therefore be smaller than our findings suggest or even negative. In contrast, emission savings related to halving avoidable consumer food waste might be even underestimated as also unaccounted emissions might be saved due to the declined food demand.

Applying a PE model, we do not fully account for rebound effects. Consumers may use expenditure savings to consume higher value, non-food products (Kuiper and Cui, 2020; Philippidis et al., 2019) which might offset the agricultural emission reductions. Saved emissions from reduced incineration or landfilling of food waste (Birney et al., 2017) are neither accounted for in our analysis. Also, we do not consider compliance, opportunity, or policy implementation costs (De Laurentiis et al., 2020). Costs and emissions related to setting up a food waste handling, collection and treatment system in order to valorize food waste as animal feed (Spinelli and Corso, 2000) are roughly captured in the price sensitivity analysis. In our analysis we abstract from implications related to the choice of food waste treatment technology and intra-annual fluctuations regarding the amount and composition of available food waste. Since FWF is complemented with conventional feed to fulfill nutrient requirements of pig diets in the model, we do not assume a deterioration of meat quality. We do not account for potential differences in the willingness to pay for pork produced with FWF (Kurishima et al., 2011). The national average consumers and producers in the model are represented as rational, economic agents and their behavior is calibrated based on historic data. Heterogeneity in food intake, waste, or rebounds (Chitnis et al., 2014) between consumers is beyond the scope of this analysis. At country level we account for a potential link between affluence and food waste behavior. However, the validity of this relationship is subject to ongoing discussions (UNEP, 2021) and requires further research (Appendix C). Except for food waste-related behavior, preference changes toward more sustainable consumption and production choices are not accounted for in our analysis. Considering diets shifting increasingly toward plant-based choices (Saari et al., 2021), other valorization options for food waste than the reuse as animal feed, such as the production of fertilizers (Slorach et al., 2019), could become increasingly relevant. While our results are specific to the EU agricultural-food market, the intervention logic and the direction of effects could be transferrable to other large high-income regions.

3.5.3 *Sustainability tradeoffs and policy implications*

If we combine both interventions in the FWcombi scenario, our model projects the largest EU agricultural emission savings of our scenarios (4%). By accounting for market and trade feedbacks, we find additional emission savings abroad as consequence of such a considerable decline in EU demand, whereas the valorization of plant-based food waste as pig feed promises comparably small environmental benefits.

The consideration of market feedbacks results in lower environmental benefits from food waste reduction and valorization within the EU compared to the embedded impacts in the previously wasted food. Globally however, our assessment shows that reducing avoidable consumer food waste might achieve an over-proportional reduction of GHGE due to considered regional differences in emission-efficiencies of agricultural production. Given the global nature of the problem, GHGE reductions contribute to climate change mitigation wherever they are achieved. In contrast, the described trade feedbacks limit the reduction of local environmental pollution like nitrogen surpluses. Therefore, complementary production-side interventions could be implemented to achieve environmental improvements “domestically”.

EU food waste reduction and valorization lead to lower food prices across product groups which facilitates food access for net consumers, also in low-income trading-partner countries. However, for consumers who already exceed recommended intake levels of some foods (Mertens et al., 2018), this can have undesirable impacts on nutrition.

Trade effects resulting from potential EU consumer food waste policies can cause increases in exports and competition for producers abroad. Overall, the reduced food demand related to a reduction in food waste negatively affects the income of net producers in the EU — and via trade effects also elsewhere.

If FWF is available at low costs, this can be beneficial for pig farmers. However, policy-makers need to consider that FWF appears only limitedly competitive compared to conventional feed due to its assumed low protein content and could therefore require subsidization unless a price premium is expected for circular pork. Furthermore, if FWF is available at a competitively low price, EU pig production might increase. This, accompanied by additional demand for imported protein feed, could offset intended environmental improvements. Our results question whether available plant-based food waste biomass would suffice for setting up a competitive valorization system for pig feed. If this is politically intended, potential benefits should be pre-assessed subject to valorizing only unavoidable food waste and a declining demand for animal products to not compromise other policy aims.

The described tradeoffs will, to some extent, be inevitable in the transformation to a more sustainable EU food system. These tradeoffs must be accounted for in any food waste policy implementation to make these attempts a success across sustainability dimensions. This includes the consideration of additional policies that 1) account for indirect income effects for producers in the food chain in and outside the EU, 2) steer consumers toward compliance with dietary recommendations, 3) avert additional imports of emission-intensive protein feed, and 4) ensure that food waste policy packages are coherent to prevent the creation of unintended competition for food waste biomass.

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3.7 Appendix

Supplementary material associated with the article underlying this chapter can be found, in the online version of the article, at https://doi.org/10.1016/j.resconrec.2022.106545.

3.7.1 *A. Supplementary figures*

eSlide: Figure A.1. EU average per capita food demand divided by intake, avoidable and unavoidable waste in the Baseline in 2030. The interactive figure is provided in the online supplementary material of the article.

eSlide: Figure A.2. Quantitative flows from EU production and imports to EU demand positions and exports by product groups. Scenario-related additional (in green) and omitted (in orange) flows for the FWcut scenario, the FWfeed scenario, and the FWcombi scenario compared to the Baseline in 2030. The interactive figure is provided in the online supplementary material of the article.

3.7.2 *B. Supplementary model results*

Supplementary model results are provided in the online supplementary material of the article.

3.7.3 *C. Supplementary information*

Supplementary information on CAPRI modelling system are provided in the online supplementary material of the article.

The CAPRI model

The Common Agricultural Policy Regionalized Impact modelling system (CAPRI) is built for comparative static policy and market impact assessments covering global and, for EU member states, also regional scales (Britz and Witzke, 2014). Comparative static implies that we compare the results of the Baseline in a projected year (i.e., 2030 in this study) with the changes resulting from a policy scenario in that same year. A comparison of the development over time is not subject of this study. CAPRI contains a spatial, non-stochastic global multi-commodity model that is calibrated on historic statistical production and consumption data. It is defined by a system of behavioral equations differentiated by commodity and geographical units representing profit or utility maximizing economic agents. Consumer demand is based on generalized Leontief expenditure functions (Ryan and Wales, 1999). Resulting indirect utility functions depend on prices and increase in income. Underlying price elasticities of demand are based on Muhammad et al. (2011), disaggregated to the product level used in the model, and adjusted in the calibration to comply with microeconomic theory (Britz and Witzke, 2014). Table 3.1 exemplifies the range of resulting own- and cross-price elasticities of demand for CAPRI meat products on EU average.

Table 3.1 EU own- and cross-price elasticities of demand for meat products

	Beef	**Pork**	**Poultry**	**Sheep and goat meat**
Beef	-0.55	0.15	0.1	0.02
Pork	0.07	-0.5	0.09	0.01
Poultry	0.1	0.2	-0.62	0.02
Sheep and goat meat	0.09	0.15	0.11	-0.61

Note: Demand elasticities calculated as the unweighted mean of EU member state values for the Baseline scenario in 2030.

The budget share devoted to food purchases is responsive to prices but demand functions also include an exogenous component that may be interpreted as minimum food consumption commitments (Britz and Witzke, 2014). Depending on the resulting elasticities, changing food prices do not only change the composition of food purchases but also the overall spending on food products from the household budget.

The consumption side is represented by an average national consumer. Subnational heterogeneity between consumers and distributional impacts on demand within countries are not accounted for. Trade flows are modelled in a two-stage demand system which allows for a differentiation between domestic sales and imports as well as between imports of different origin (Armington, 1969). This global model is linked to regional programming models ('supply models') for EU regions maximizing farm income subject to the market prices provided by the global 'market model'. The availability of land, compliance with EU and national agricultural policies, and the interplay of soil nutrient needs, feed requirements in line with animal nutrition, and livestock production serve as boundary conditions for EU agricultural production in the modelling system.

Food waste representation

As also described in Section 3.3.2 of the main paper we advance the representation of consumer food waste in this study compared to the previous standard CAPRI settings. The standard version is based on consumer food waste shares differing by world region and product group (FAO, 2011) and adjusts waste shares residually to ensure that average calorie intake remains within reasonable limits.

In this study we account for a distinction between avoidable and unavoidable waste parts as these are central to our policy scenario design. We also account for a relationship between wealth and food wasting behavior established in previous studies (Verma et al., 2020) and to this extent account for a development in food waste behavior over time.

Verma et al. (2020) estimate a positive relationship between affluence (i.e., per capita GDP in 2005 USD) and food waste expressed as

$$w_i = -4573 + 557\ \ln\left(GDP/cap_i\right)$$

with $w_i = consumer\ food\ waste\ in\ kcal/cap/year$.

We account for differences in currencies and inflation between the data underlying this equation and the way GDP is represented in CAPRI. Future population and GDP developments in the simulations are based on EUROSTAT/FAOSTAT projections (adopting the macro variable assumptions from European Commission et al., 2021) and thus exogenous to CAPRI. Historical food demand in CAPRI is informed by available food per capita provided by Eurostat and FAO food balance sheets which includes waste at the consumer stage (FAO, 2001). For consistency, we do not only include this relation between food waste and affluence in the Baseline, but already in the database consolidation and market calibration.

With this approach, we relate total wasted calories to GDP for each region. Based on the share that a product group previously had, according to historical data, in the total calories wasted we distribute the estimated sum of wasted calories from the above equation across product groups. For some regions and product groups this approach would result in unreasonable waste shares smaller than zero or larger than one. Therefore, we set the boundaries that waste shares must lie between 0.01 and 0.7 to ensure reasonable outcomes.

The finding that previously established rates of consumer food waste were considerably underestimated as shown in Verma et al. (2020) is also supported by the Food Waste Index Report 2021 (UNEP, 2021). However, the report concludes that middle-income countries have comparable consumer food waste quantities as high-income countries and thus questions the relationship between affluence and food waste underlying in our analysis. However, both approaches differ in their unit of analysis (calories versus kilograms wasted). Nevertheless, if middle-income countries indeed have comparable food waste shares to high-income countries, our approach likely underestimates consumer food waste shares in middle-income countries. Thus, the global food waste representation in CAPRI should be revised for future analyses to reflect further research findings regarding food waste measurements and drivers. The presented scenario analysis in the underlying study is limited to EU policies and changes in EU consumer food waste are at the heart of our analysis. For EU countries, we believe our adjusted food waste representation improves the previously used settings with a more explicit, transparent, and literature-based approach. Furthermore, in our comparative static scenario comparison this affluence link has no impact besides providing the Baseline waste shares. The food waste policy impacts in our assessment should thus remain valid in sign.

Scenarios

In our FWcut scenario we take the baseline food waste shares wsh and reduce the avoidable food waste shares by 50%.

$$wsh_{av,i,p,cut} = wsh_{av,i,p,bas} * 0.5$$

The total waste share declines consequentially.

$$wsh_{tot,i,p,cut} = wsh_{av,i,p,cut} + wsh_{unav,i,p,bas}$$

Technically, this is implemented as a preference shift resulting in changing food purchases for human consumption in the form of a change factor $HCONch$ which is multiplied with human consumption quantities at simulation stage.

$$HCONch_{i,p,cut} = (1 - wsh_{av,i,p,bas}) \,/ (1 - wsh_{av,i,p,bas} * 0.5)$$

with $tot = total\ waste,\ av = avoidable\ waste,\ unav = unavoidable\ waste,$
$i = \ EU\ MS, p = product,\ bas = Baseline\ scenario,\ cut = FWcut\ scenario$

This adjustment is only implemented for EU member states. Food waste shares for non-EU countries remain as in the Baseline scenario. For EU member states food waste *shares* are fixed as shown in the preceding calculation and do not change in response to market feedbacks. However, reduced purchases of previously wasted food will usually cause a drop in consumer prices on the market. The purchased quantity is *not* fixed with the preference shift. Lower prices set an incentive to again increase purchases to some extent in line with price-elasticities described earlier, which often is referred to as rebound effects (Qi, 2018). Food waste shares are applied to the resulting purchases to compute the implied calorie consumption based on simulated consumption quantities. The resulting change in intake and avoidable food waste *calories* can deviate from the 50% reduction in the avoidable waste shares, triggered by indirect price effects. Since GDP is exogenous and does not change in the policy scenario compared to the Baseline, the affluence link is not affected. However, the preference shift implies that with less food waste a larger share of the given consumer income could be spent on non-food items. The budget share spent on food however reacts to prices as implied by the underlying elasticities. For our FWfeed scenario, we calculate the share of nutrients that annual plant-based consumer food waste can replace in required nutrients for animal nutrition, $FWnutsh_{i,n,a}$, for each EU member state. Food-specific energy and protein contents available to pig nutrition are aligned to those underlying in van Hal et al. (2019) and summarized for CAPRI food groups in Table 3.2. Since we are missing market data to implement food waste feed (FWF) as a marketed product, we technically implement the FWF use by reducing the required nutrients to comply with animal nutrition, $animReq$, to those that are additionally needed from conventional feed

$$animReq_{i,n,a,feed} = animReq_{i,n,a,bas} * (1 - FWnutsh_{i,n,a})$$

with $i = EU\ regions,\ n = nutrient\ (protein,\ net\ energy,\ lysine),$

$a = pig\ production\ activity\ (pig\ fattening,\ pig\ breeding),$

$bas = Baseline\ scenario, feed = \ FWfeed\ scenario$

In the sensitivity analysis, we vary the available food waste amount and thus also $FWnutsh_{i,n,a}$ and $animReq_{i,n,a,feed}$. We introduce an additional parameter to account for potential costs arising to the farmer for using food waste as pig feed. Costs are related to conventional costs for feed net energy and are production activity-specific (i.e., differ for pig fattening and pig breeding).

Table 3.2 Food waste nutrient contents available to pig nutrition as fresh matter per kg in line with van Hal et al. (2019)

Product group	**Net energy**	**Crude protein**	**Lysine**
Wheat	10.55	0.089	0.0023
Barley	10	0.07	0.0027
Maize	11.5	0.053	0.0017
Rye and meslin	9.98	0.065	0.0028
Oats	8.41	0.067	0.0034
Other cereals	10.675	0.0735	0.00165
Rice	8.65	0.045	0.0024
Potatoes	2.2244	0.007482	0.000546
Other roots	10.175	0.007	0.0007
Sugar	13.4	0	0
Pulses	9.375	0.1665	0.01235
Soya	13.9	0.153	0.01082
Soya oil	33.78	0	0
Other fruits	1.9377375	0.004552119	0.000144856
Other oils	33.8325	0	0
Sunflower seed	14.64	0.156	0.005
Sunflower oil	33.87	0	0
Rapeseed	16.69	0.132	0.0079
Rapeseed oil	33.89	0	0
Other oilseed	14.64	0.156	0.00535
Palm oil	32.815	0	0
Olives	9	0.019	0.00047
Olive oil	33.75	0	0
Tomatoes	0.6	0.00759402	0.00058474
Other vegetables	1.1922	0.008655395	0.000628411
Citrus fruits	1.7064	0.0042107	0.000103648
Apples and pears	1.707375	0.00300027	0.000231021
Coffee	4.314375	0.0133104	0.00092
Cocoa	4.314375	0.0133104	0.00092

Greenhouse gas emission impacts

Changes in greenhouse gas emissions are calculated for the projected agricultural production settings (Britz and Witzke, 2014; Leip et al., 2015).

These impacts are specific to the projected *production activity changes* related to the each respective scenario by referring to emission inventories and nutrient balances based on IPCC (2006) and Leip et al. (2011). While we could not account for any more recent refinements of IPCC emission factors (IPCC, 2019), the 2006 factors we apply are in a similar range so that we believe the scope and direction of our findings to remain reliable.

For comparison purposes, we use the *product-based* emission coefficients in CAPRI in addition (Weiss and Leip, 2012) to calculate the emission reduction potential in our food waste reduction scenario, FWcut, that could be expected when market feedbacks are *not* considered (FWcut no market feedback scenario), like it is often the case in LCA-based studies. The underlying calculation is relatively straightforward for the FWcut scenario (i.e., multiplying reduced quantities of avoidable food waste with product-based emission coefficients). In contrast, we cannot simply transfer this approach to the food waste feed scenario, FWfeed, as more detailed assumptions would be needed regarding how to allocate product-based emissions along the value chain. This is neither the focus of our analysis nor the core strength of the modelling system.

Both, activity-based and product-based emission coefficients relate to non-CO_2 agricultural greenhouse gas emissions and do not capture emissions from transport, processing, or deforestation and more generally other LULUCF effects (from Land Use, Land Use Change and Forestry).

System boundaries

The greenhouse gas emissions that are integrated in the model relate to non-CO2 emissions. Carbon emissions from transportation, industrial processes, or those related to land conversion (e.g., deforestation) are not accounted for in the model version underlying this study. While the total areas of cropland, grassland, forests, and other land are covered, a full accounting of carbon effects in the LULUCF sector would also require information on all land conversions, to be represented in future model versions.

Food waste treatment and collection cannot be directly assessed. Related environmental impacts to these processes cannot be captured. The potential effect that these production steps would have on costs for the pig producing farmers and thus also on the final product prices are assessed as part of the sensitivity analysis.

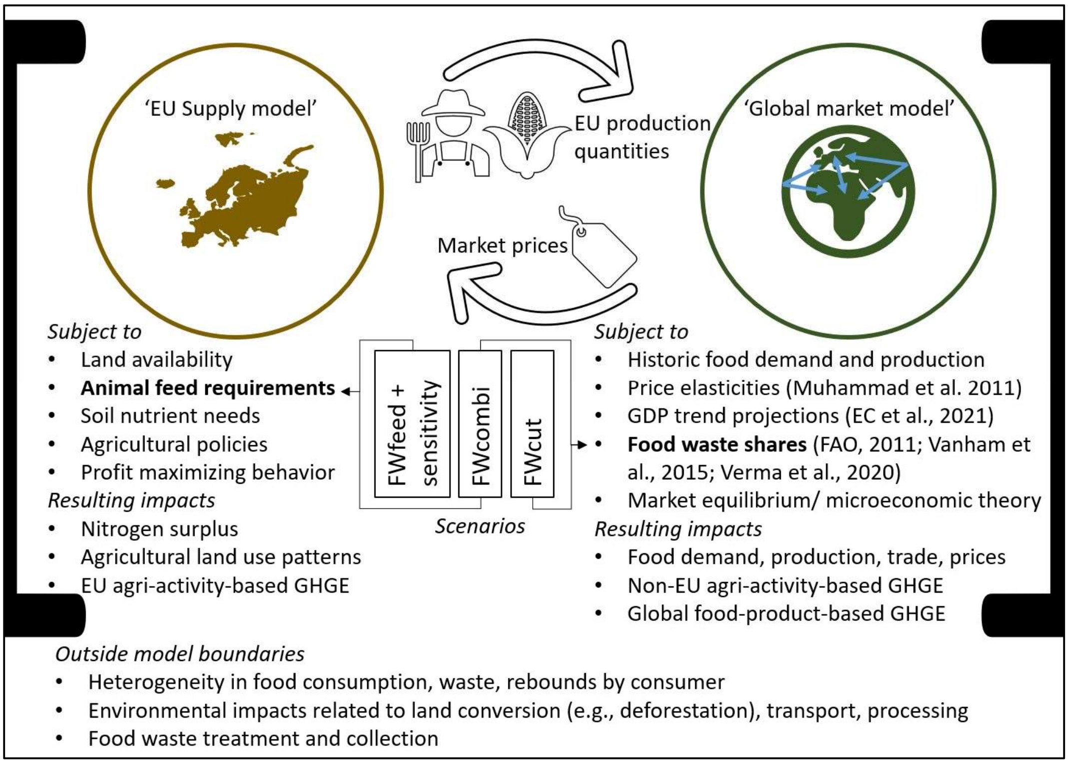

Figure 3.6 CAPRI model structure, system boundaries and feedback loops.
Note: GHGE=Greenhouse gas emissions.

On the demand side, subnational impacts are not captured in the model. Implications on food affordability and access for different consumer groups can only be inferred from resulting market quantities and prices, but no direct assessment is possible at this level. Consumer (group) differences in food consumption, waste behavior, and rebound effects or food-related implications on their nutrition can only be deduced for an exemplified average national consumer.

Figure 3.6 summarizes the described CAPRI model structure, the system boundaries and the feedback loops between the model components as described in the paper and in this supplementary information.

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Chapter 4
CAP measures towards environmental sustainability – Trade opportunities for Africa?[‡]

Abstract: Environmental sustainability is a core aspect of the proposed future EU Common Agricultural Policy (CAP). Policy changes must not compromise socioeconomic development in low-income countries, whereas the extensification of EU agriculture may also create trade opportunities abroad. We apply a global agricultural-economic model to assess EU-African trade-related impacts of potential, environmentally motivated CAP changes. Restrictions on livestock density and nitrogen application reveal reduced EU production levels of meat. This lowers the EU's agricultural environmental burden and share in agricultural trade flows to Africa. However, overall food supply in Africa is not projected to deteriorate substantially, as imports from other world regions and increasing domestic production fill the gap. While this weakens the global emission reduction potential, net-livestock producers in Africa may benefit from increasing producer prices. How far potentials for domestic production and trade can

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Credit: Catharina Latka: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. Thomas Heckelei: Conceptualization, Writing – review & editing. Arnim Kuhn: Conceptualization, Writing – review & editing. Heinz-Peter Witzke: Conceptualization, Software, Resources, Writing – review & editing. Lukas Kornher: Conceptualization, Writing – review & editing.

be used in African regions depends at least partly on their competitiveness vis-á-vis substituting importers.

Keywords: agri-environmental policies, CAP reform, coupled payments, EU-Africa-trade, sustainable development

4.1 Introduction

The discussion on the post-2020 reform of the Common Agricultural Policy (CAP) focuses on environmental and climate targets for the EU. These are laid down in the United Nation's Sustainable Development Goals (SDGs) (UN, 2015) and the Paris Agreement (UN, 2016). The political relevance of these goals is spelled out in the proposal of a "European Green Deal" (European Commission, 2019a) for climate neutrality by 2050. While the future CAP shall increasingly serve environmental targets, implications on sustainable development in trading partner countries have not been central to the CAP either in the past or in the current reform discussion. The discussed CAP measures may substantially impact EU production and, thereby, the agricultural trade with partner countries. The implications for African countries could potentially affect the achievement of SDGs that need to be considered in the EU's agricultural policy design (European Commission 2017; European Council et al. 2017). In order to ensure coherence between EU policies and international commitments, it is necessary to assess potential tradeoffs and synergies of policy targets.

This paper applies an agricultural-economic simulation model to analyze the impacts of potential CAP policy reforms on EU production and trade with Africa. The CAP scenarios that we consider are designed with a focus on environmental sustainability. Specifically, we assess a change in direct payments in favor of more extensive production and a shift toward stronger regulations on animal density and nitrogen application. This paper addresses the question of how policy-induced EU agricultural production changes may affect African trade relations and production patterns. We explore how far potential policy changes under an EU CAP reform may lead to trade opportunities for African producers, if at all. Our results also shed light on potential implications for African consumers and on the environmental achievements targeted through policy design.

In October 2020, the EU parliament passed the cornerstones of the CAP reform including the allocation of at least 30 per cent of the overall budget to climate objectives (European Commission 2020a). The EU Commission's proposal contains a variety of reform suggestions to ensure that the future CAP will contribute to the objectives of the Green Deal (European Commission 2018, 2020a). The Council and the EU Parliament confirmed the new measures in parts. However, some details regarding the level of minimum spending on eco-schemes or the environmentally friendly requirements that farmers must fulfil when receiving income support were still under debate at the end of 2020 (European Commission 2020a).

Sustainable growth and development progress in Africa are key components for meeting the global SDGs by 2030 (Kedir et al. 2017; Schwerhoff and Sy 2017). While challenges persist in Africa to increase agricultural productivity and efficiency in local value chains necessary to reduce food insecurity and poverty, the region's involvement in global agri-food value chains has expanded rapidly (Feyaerts et al. 2020). According to mainstream economic theory, exploiting comparative advantages in trade relations offers great welfare and development potentials (Kanji and Barrientos 2002). However, Desai and Rudra (2019) find that the agricultural trade impacts on poverty in developing countries are ambiguous and depend on the net trade status of a country. Also, global economic crises can weaken the reliability of trade flows and, thus, increase the necessity of at least ensuring partial self-sufficiency and a diversified food supply in staples (Chen and Villoria 2019; Puma et al. 2015). The EU continues to be Africa's most important trading partner, roughly covering one-third of African imports and exports in 2018 (Eurostat 2019). Food commodities represent about one-tenth of African imports from and exports to the EU (Eurostat 2019).

Thus, EU agricultural policy changes need to be assessed with respect to their potential consequences for trade with Africa, for sustainability, and for development. This paper contributes by providing an assessment of environmentally motivated CAP changes with a focus on their impacts in

African trading partner countries. In our results, changes in the CAP payment structure do not show a strong impact on trade, but restrictions on livestock density and nitrogen applications in the EU affect trade flows to Africa. By analyzing bilateral trade flows in a global setting, we find that increased trade with non-EU trading partners fills most of the occurring trade gap and domestic production in Africa also increases to some extent. By scenario design, we can see environmental improvements in the EU, but emission leakage through trade reduces some of the achievements on the global scale. Our assessment builds on existing simulation studies while considering the ongoing reform debate. Furthermore, we add to the literature by putting the analysis in the context of policy coherence with respect to different domains, namely agriculture, development and trade.

The paper is structured as follows. Section 2 provides an overview on agricultural trade between the EU and African countries and existing evidence on how this is influenced by the CAP. Also, CAP relations to environmental sustainability are pointed out in this section. Section 3 provides the model description and the scenario design. Our results focus on adjustments in prices, production, consumption, trade, and environmental impacts in the EU, in its African trading partners, and in part globally (Section 4). Limitations inherent to the modeling approach, underlying assumptions and their likely implications for our results are discussed in Section 5 and the conclusions from our assessment are derived in Section 6.

4.2 CAP relation to EU–Africa trade and sustainability

There has been an increase in the traded quantity of several agricultural products between the EU and Africa since the beginning of the twenty-first century (Figure 4.1). With respect to level and growth in African imports from the EU, cereals stand out among product categories. Moreover, imported quantities of vegetables and fruits, and meat by African regions from the EU increased between 2000 and 2013. Meat imports are demanded almost entirely from Sub-Saharan Africa. The traded quantities from Africa to the EU do not reach the high level of cereal inflows. Still, there is a strong growth trend in fruit and vegetable exports from Africa to the EU, specifically from North Africa. The second largest export quantity is the

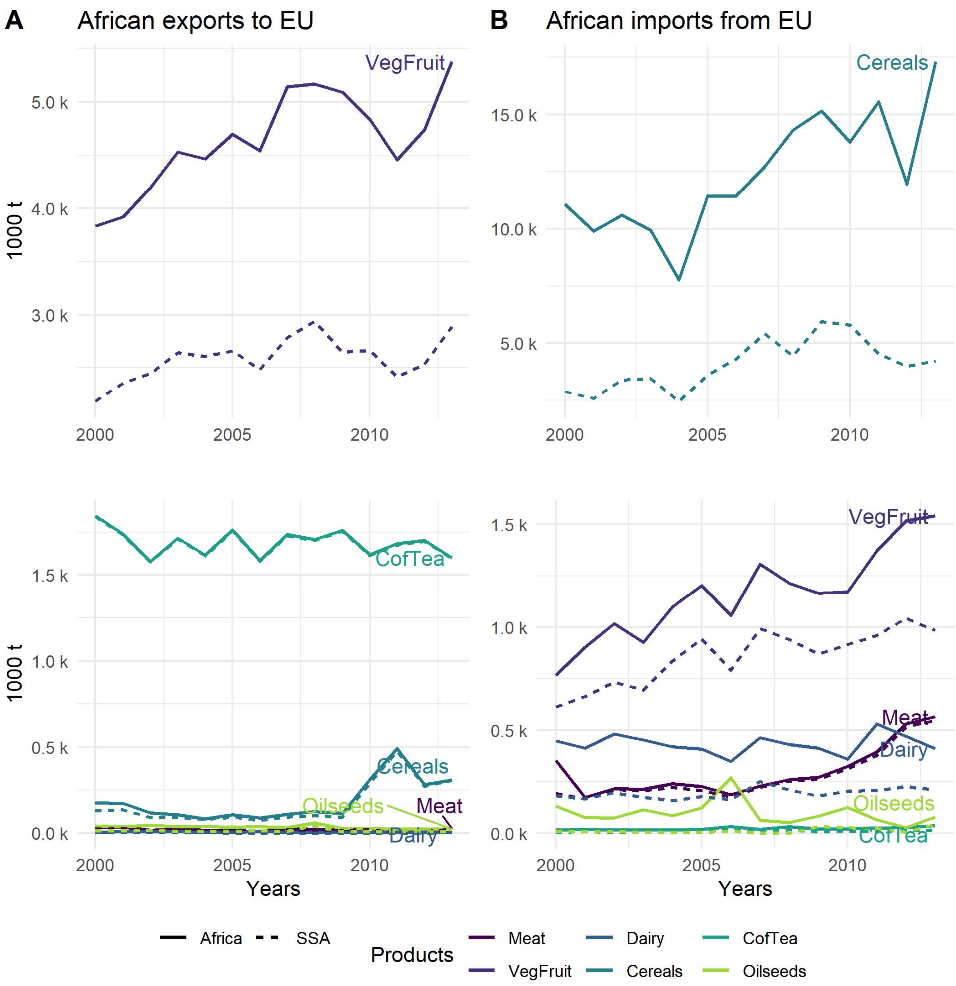

Figure 4.1 Agricultural trade flows (in quantities) between the EU and Africa with explicit differentiation of Sub-Saharan Africa (SSA) between 2000 and 2013. Note: CofTea = Coffee, tea, cocoa aggregate. VegFruit = Vegetable and fruits. Dairy = Dairy products. All products in primary equivalents and thus including processed foods. Source: Bilateral trade quantities are taken from FAOSTAT (2015) and processed to CAPRI aggregates under consideration of data quality applying a trust indicator for trade notifications from different reporters.

high value group of coffee, cocoa and teas sourced in Sub-Saharan Africa. Despite its comparably high level, no clear increasing trend is visible. A sudden increase in cereal exports from Sub-Saharan Africa to Europe is evident around the year 2010.

Agricultural trade between the EU and Africa has been criticized for negatively impacting African agricultural producers (Laroche Dupraz and

Postolle 2013; Weible and Pelikan 2016). In this context, it is suspected that the CAP aggravates barriers to development through implicitly subsidizing exports (Reichert and Thomsen 2018). A recent publication by Flaig and Boysen-Urban (2019) assesses the flow of EU agricultural subsidies along the respective value chains and concludes that about 2 per cent of those payments are forwarded to African trading partner countries indirectly via price effects. Consequently, opposite welfare implications arise for African net producers and net consumers of the respective commodities (Rudloff and Brüntrup 2018).

A reduction of the direct payments and their redistribution in particular to sustainability measures are discussed in the reform proposal (European Commission 2018). The CAP's "New Green Architecture" allows for the possibility of setting the necessary incentives through agricultural-environment-climate measures or eco-schemes (European Commission 2019b; Matthews 2018). According to the literature, only minor impacts on EU production and trade are related to the currently existing direct payments schemes (Boysen et al. 2016; Philippidis et al. 2016). However, marginal areas are more likely to be kept in production, which increases EU agri-food net trade surpluses (Brady et al. 2017). According to Matthews (2018), a redistribution of direct payments to small and medium-sized farms could reduce EU exports while increasing agricultural imports to the EU, also from low-income countries. Bureau and Swinnen (2018) argue that despite limited incentives from direct payments for agricultural production and trade, the world market is still impacted through policy effects on welfare and farmers' risk.

Animal production is the main contributor to environmental pollution from agriculture in the EU, and it bears the greatest potential for reducing greenhouse gas emissions from the sector (Herrero et al. 2016; Leip et al. 2015). Applying both mineral and organic fertilizer beyond the cultivars' nutrient needs contributes to nitrogen pollution of the soil, adjacent water bodies, and the groundwater (van Grinsven et al. 2012; Sutton et al. 2011). This is partly driven by the spatial disconnection between feed and livestock production in global food systems that disrupts nitrogen cycles and can cause local nitrogen oversupplies (Lassaletta et al. 2014). Therefore, nitrogen surpluses are especially present in regions of high animal density (Svanbäck et al. 2019). The European Commission's proposal on the CAP reform states that the policy framework shall more strongly consider 'the need to improve farms sustainability, and in particular the nutrients management' (European Commission 2018, paragraph 22) as well as 'the response of EU agriculture to societal demands on […] animal welfare' (European Commission 2018, specific objectives (i)). Restricting animal density and nitrogen application can potentially become part of the future EU agricultural policy under animal welfare and environmental considerations.

4.3 Methods

In order to assess potential impacts of future policies, applying ex-ante simulation tools is an established method. Alternative policies can be tested as scenarios within the model setup. In this case, the results of the reference scenario are compared with those of the alternative policy shocks for a future point in time. The Common Agricultural Policy Regionalized Impact Modelling System (CAPRI) is a state-of-the-art and widely applied economic model (e.g. Frank et al. 2019; Himics et al. 2020). Its features and the scenario specifications for the present study are explained in subsections 4.3.1 and 4.3.2.

4.3.1 *Model description*

CAPRI (Britz and Witzke 2014) is a global, agricultural-economic, partial equilibrium model that provides a detailed representation of the EU agricultural sector (Appendix A, Tables 4.7 and 4.8). The latter is simulated by regional programming models that maximize farm income subject to given market prices, subsidies, and other payments. The availability of land, compliance with regulations, and the interplay between soil nutrient needs, feed, and livestock serve as boundary conditions for agricultural production. Supply-side reactions reflect medium-term adjustments under the current model specifications. Thus, variable inputs like feed and fertilizer adjust to changed incentives, whereas capital and labor are less responsive. The EU supply model is linked to a second module, the global market model, via the exchange of production quantities and market price changes. In this global model, consumers, producers and traders interact as economic agents based on microeconomic theory. Trade flows are modelled in a two-stage demand system based on the "Armington (1969) assumption" that differentiates between domestic sales and imports as well as between imports of different origins. The underlying reasoning in the CAPRI implementation is that consumers substitute less easily between domestic and imported goods than they do between imported goods of different origins. In addition to effects on quantities and prices, a number of environmental indicators (e.g., nutrient surpluses and greenhouse gas emissions from the agricultural sector) are also calculated in the modelling system.

4.3.2 *Scenario design*

The chosen reference scenario is based on the "Agricultural Outlook" of the European Commission (2016). In this scenario, the current CAP is extended until 2030. Technological progress, and population and economic growth are projected based on trend assumptions. As this scenario is based on the currently implemented EU agricultural policy, it can be interpreted as a "business-as-usual" (BAU) scenario.

While direct payments to farmers are organized within the first pillar of the CAP, the second pillar is designed to support rural areas within the EU. Second pillar measures are modeled in line with the actual regulations covering "Less Favoured Area" payments, agricultural-environmental measures, or "Natura 2000" support for biodiversity protection. In the first alternative policy scenario, we analyze a reduction of first pillar direct payments by 50 per cent (DP50) based on the respective amount paid in the BAU scenario. In this scenario, the capped direct payments drop completely out of the CAP budget. The reduction is implemented as a cut in all measures in the first pillar of the CAP, including decoupled direct payments and voluntary coupled support. While decoupled payments are independent of production levels, some degree of coupling remains because land receiving payments is supposed to be kept in good agricultural and environmental condition and must not be abandoned.

Cutting Pillar I payments in half is a rather unlikely setting; still reductions in the CAP budget are part of the EU reform debate. Therefore, this potentially extreme case is tested to assess the implications of potential CAP budget cuts in the EU for agricultural trade and environmental sustainability.

Our second scenario is designed as a transfer of the budget freed-up by cutting the payments previously related to CAP Pillar I to measures with a focus on extensive crop production in Pillar II (DPTRANS). In the implementation, extensive crop production is represented as a production technology requiring fewer inputs that is, however, as well reflected in lower yields. Also, the shift of some Pillar I payments for a broad range of agricultural activities to financial support of mainly crop-producing activities induces some changes in the agricultural sector.

The scenario is inspired by the proposal of allocating 30 per cent of the Pillar I payments to schemes for organic farming, permanent grasslands, or marginal areas (European Commission 2018). In the discussion on the future CAP, Matthews (2018) describes a planned transfer of 15 per cent of the Pillar I national ceilings to environmental and climate measures in the second pillar. Our scenario exceeds these suggestions and the probable CAP changes to emphasize the potential of such a transfer.

Areas of high animal density are hotspots for nitrogen surpluses and related soils and water pollution (Jørgensen et al. 2018). To account for regional heterogeneity regarding nutrient balances, we restrict maximum animal density in a further scenario (LSMAX) to the respective local soil nitrogen needs in the BAU scenario. In detail, we simulate this scenario by dividing the regional nitrogen need per hectare taken from the CAPRI nutrient balances by the regional excretion per livestock unit in a region based on the BAU scenario to define the maximum livestock density per hectare. In the regional programming models, this upper bound is implemented as an inevitable constraint.

In this way, we prevent a nutrient undersupply of the soil and related strong negative consequences for yields and plant productivity (Csathó and Radimszky 2009). The shock is attenuated in areas with low soil nitrogen needs by implementing a minimum boundary of 0.6 livestock units per ha.

This limit lies within the boundaries that Buckwell and Nadeau (2018) describe as sustainable animal density for ruminants. In Appendix A, we provide an overview of livestock densities before and after the restriction across EU regions (Table 4.9 in Appendix A).

While EU nitrogen surpluses have generally declined in hotspot areas, strong surpluses persist and the overall surplus level in the EU remains high by international comparison (van Grinsven et al. 2012; Potter et al. 2010). In the CAPRI modelling system, we simulate an enforced Nitrates Directive by imposing soil nitrogen surplus limits of 50 kg N ha^{-1} a^{-1} (NITR). Fertilizer applications influence the nutrient balances in the model and are configured in a way that the soil nitrogen surplus must not exceed the stricter limit. The resulting reduction in nitrogen surpluses varies by region and its nitrate vulnerability status. For some regions, nitrogen surpluses even reduce to one-eighth of the surplus level in the BAU scenario. This enforcement is implemented on top of other nitrate directive components taken from existing regulations without further adjustment in our scenario design (e.g. a 170 kg N ha^{-1} a^{-1} manure application limit, regional maximum fertilization specifications based on EU member state regulations).

Furthermore, we assess the restriction of animal density and nitrogen application in a combined approach (NCOMBI). Practically, we combine the scenarios by simulating the nitrogen surplus limit of 50 kg N ha^{-1} a^{-1} and the livestock density restriction in one run. Since the livestock density restriction is designed based on livestock numbers and nutrient balances from the BAU simulation, the specification of the constraint is not affected by changes in the actual nitrogen balances of the current scenario run. However, the nitrogen surplus as such (even though not the implemented policy restriction) can be affected by the livestock restriction. Also, in the scenarios NITR and NCOMBI, the imposed constraints on nitrogen surplus may contribute to lower livestock densities. An overview on the scenarios used in this study is provided in Table 4.1.

Table 4.1 Scenario overview

Scenario group	Acronym	Description
Business-as-usual	BAU	Reference scenario
Adjustments of direct payments (DP)	DP50	CAP Pillar I payments reduced by 50%
	DPTRANS	Budget reduced in DP50 transferred to CAP Pillar II
Restrictions of animal density and nitrogen application	LSMAX	Livestock density restriction
	NITR	Surplus nitrogen limitation
	NCOMBI	Combination of LSMAX and NITR

4.3.3 *Indicators*

In the scenario assessment, we focus on relevant impacts on EU–Africa trade flows. For the reference scenario, agricultural product trade flows are analyzed for the EU and the African model regions in 2030. Policy scenario impacts are assessed on the basis of changes in consumer and producer prices, and production, consumption, import and export quantities. Potential implications for welfare and food security are pointed out, although in the light of limited model representation. Substituting trade flows to Africa from other countries are considered in this analysis as well. We also investigate changes in land-use, nitrogen surpluses and agricultural greenhouse gas emissions given that the policy changes simulated aim at increased environmental sustainability.

4.4 **Results**

Africa is projected to be a net importer of a number of agricultural products in the BAU scenario in 2030. African production cannot satisfy the domestic demand especially for wheat, rice, and most oil products for human consumption, processing, and animal feed. Furthermore, the demand for meat and certain dairy products (especially milk powders) is mainly met by imports. Africa’s self-sufficiency shares for human consumption of cereals, vegetables, fruits, oilseeds, and dairy products in the BAU projection for 2030 are provided in Table 4.10 (Appendix B). Agricultural trade flows between the EU and Africa in the BAU scenario demonstrate the projected current trend for the year 2030.

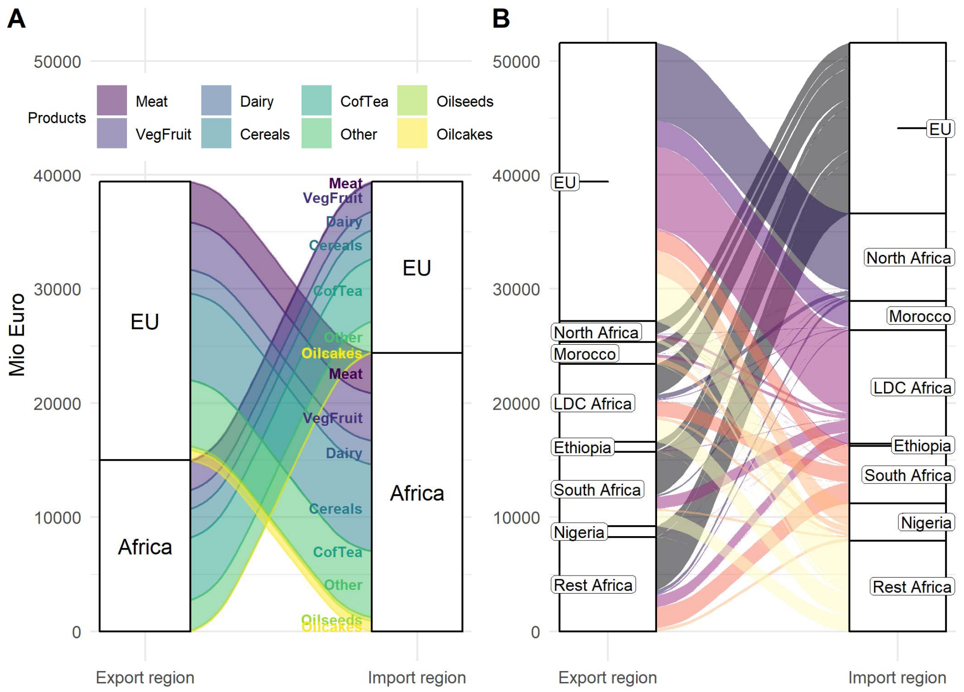

Figure 4.2 EU-African agricultural product trade flows in BAU 2030 Note: Agri-trade flows between the EU and Africa by product groups (A) and between the EU and African CAPRI regions and their bilateral trade flows (B) as aggregated monetary value in million Euros. LDC Africa = "Least Developed Countries in Africa" region group in CAPRI. Rest Africa = region group in CAPRI including the remaining African countries, not captured in one of the other explicitly shown regions. CofTea = Coffee, tea, cocoa aggregate. VegFruit = Vegetable and fruits. Dairy = Dairy products. Other = all agricultural products not captured under the explicit groups. All products in primary equivalents and thus including processed foods. Source: CAPRI model results

For Africa, the EU is projected to be an important trading partner with a 19 per cent share of the total agricultural import value. Most African cereal imports originate from the EU. With respect to dairy and meat products, the EU's share of the total African import values is 30 per cent and 20 per cent, respectively, for these product groups. In contrast, Africa is also the dominant cereal exporter to the EU, making up 42 per cent of the total EU cereal import value in 2030. Grain maize accounts for 82 per cent of the African cereal exports to the EU. Figure 4.2 shows the EU–African trade flows as aggregated million Euros. Africa is projected to import more agricultural products from the EU than the other way around. The group of coffee, tea, and cocoa holds the highest share of EU imports from Africa in monetary terms, which is predominantly driven by cocoa trade. Among the African countries South Africa is the largest exporter to the EU, quantitatively. The North Africa region imports the most in quantities from the EU when comparing the African CAPRI regions.

4.4.1 *Adjustment of direct payments*

Halving the direct payments (DP50) only has a minimal impact on overall EU agricultural production in the modeling system (Figure 4.3). This is implied by the decoupling of payments. On average in the EU, voluntary coupled payments make up only 10 per cent of the value paid under CAP Pillar I in the 2030 BAU simulation. Since coupled support is voluntary, application rates vary between member states. Therefore, the implications of halving the payments under Pillar I differ by farming activity, member state, and the share of coupled payments received in the reference scenario.

Transferring half of the Pillar I budget to extensive measures in Pillar II (DPTRANS) has slightly different effects compared with the DP50 scenario. The payment transfer shifts production slightly toward more extensive, but also less profitable production activities. Overall, production, price, and trade reactions are weaker than in the DP50 scenario.

On average in the EU, the effects of the DP50 scenario are mainly restricted to dropping marginal land out of production. The decline of 1 –2 per cent in cereal and oilseed production is the most noticeable reduction. The drop in direct payments reduces not only the income that EU farmers receive from grazing and pasture activities but also the income related to all crop and most other livestock activities. Especially, income from beef production and dairy farming activities is affected in member states such as Sweden, Spain, Greece, or Italy, where these activities receive comparatively more support through voluntary coupled payments than in other EU countries.

If the reduced payments under Pillar I are transferred instead to financing extensive production (DPTRANS scenario), large shares of the decline in financial support under DP50 are offset on EU average. Some activities like vegetable and fruit production are supported considerably more strongly than in the BAU scenario, but related supply responses are small. A strong supply response is missing as even increased premiums remain small in the light of overall production costs for some activities. At a more disaggregated product level, larger production increases for example of pulses (+11 per cent), oats (+7 per cent), or sheep and goat meat (+4 per cent) are visible on EU average as a consequence of the increased support for related extensive production activities. Also, at the subregional level, we find strong changes remaining in terms of financial support and supply quantities, which average out at the EU level to a large extent.

Revenues for farming activities increase marginally in the DP50 scenario based on slightly higher producer prices (Table 4.2). In the DPTRANS scenario, producer price differences compared with the BAU scenario are even smaller. Also, EU human consumption remains nearly unaffected as EU consumer price changes remain below 1 per cent.

In relative terms, the occurring EU production change affects trade flows more strongly than the EU domestic market. In the DP50 scenario, the resulting decline in EU exports of cereals and, less strongly, of oilseeds and meat does not leave export flows to Africa unaffected. In the DPTRANS scenario, export changes follow a similar direction with the exception of meat and dairy products but are generally smaller in size. Declining imports from the EU are largely compensated for by increasing imports from other world regions in both scenarios. A smaller part of the supply gap is filled by increased domestic production. Overall, African production and consumption hardly change. Rising producer prices in Africa have the potential to reduce poverty and improve food security among net agricultural producers. However, for net food consumers, increasing consumer prices could worsen their food security status. Nevertheless, relative price changes in Africa that follow from a change in EU premium payments remain close to zero, so that the described potential impacts are marginal. Moreover, the average African calorie intake and consumption pattern appears unaffected by this EU policy change.

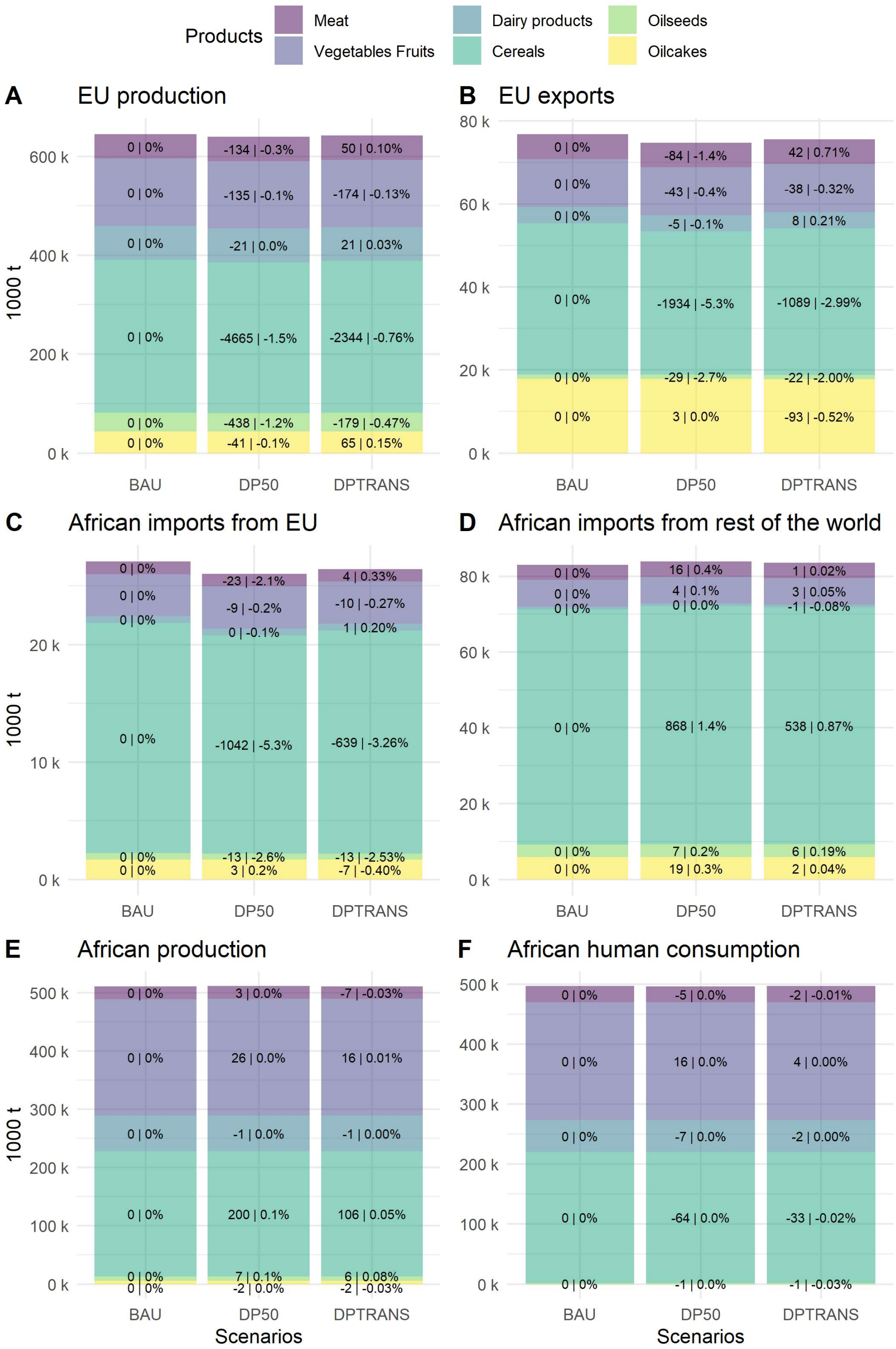

Figure 4.3 Impacts of a reduction or transfer of direct payments relative to BAU 2030 Note: Volume, absolute and percentage changes for agricultural production (A,E), consumption (F) and trade (B,C,D) for EU and Africa. All products are in primary equivalents, and thus, include processed foods. Source: CAPRI model results.

Table 4.2 Percentage price changes in EU and Africa relative to BAU 2030

	Producer price change (%)				**Consumer price change (%)**			
	DP50		**DPTRANS**		**DP50**		**DPTRANS**	
	EU	Africa	EU	Africa	EU	Africa	EU	Africa
Cereals	1.33	0.28	0.67	0.14	0.17	0.17	0.09	0.10
Dairy	0.16	0.05	-0.07	-0.01	0.12	0.05	-0.05	0.00
Meat	0.72	0.13	0.01	-0.02	0.30	0.12	-0.00	-0.01
Beef	1.70	0.14	0.86	0.05	0.87	0.13	0.44	0.05
Pork	0.45	0.17	-0.40	-0.09	0.14	0.16	-0.12	-0.10
Poultry	0.38	0.13	0.17	0.05	0.16	0.11	0.07	0.04

Source: CAPRI model results

When comparing the results by African CAPRI regions for cereal imports from the EU, percentage changes hardly differ by region and lie between −4 per cent and −6 per cent for the DP50 scenario. In absolute terms, North Africa records the strongest decline in cereal imports from the EU. The generally smaller cereal import changes in DPTRANS follow a similar pattern (see Appendix C in the Supplementary Material for further details).

Overall, EU production and exports to African countries are only affected to a minor extent with at most a change in African cereal imports from the EU of approximately 5 per cent. The results do not suggest an impact on the food security status in African countries. On EU average, a shift of payments from Pillar I to Pillar II shows even less pronounced effects on overall EU production and trade. Thus, resulting impacts are also lower on exports from the EU to African regions.

Implications for EU producers at a more disaggregated regional and product level are subsumed in these average numbers. Related distributional consequences that could follow from such a policy shift within the EU are not discussed in this study in depth. Still, for EU farmers reliant on the Pillar I support the production declines could imply their dropping-out of the market and further concentration in the sector. Whether any production reduction would materialize as a small decline by many farmers or by a complete drop-out by few cannot be distinguished by the model.

4.4.2 *Restrictions of animal density and nitrogen application*

Enforcing stronger regulations for nitrogen application and animal density restrictions implies small changes in crop and dairy production in the modeling system, whereas meat production decreases more strongly by up to 11 per cent (Figure 4.4). EU producer prices for meat in general and pork in particular increase by up to nearly 50 per cent (Table 4.3). Also, EU consumer prices for meat increase, which reduces calorie intake from meat products by 3 per cent on EU average. As the producer price constitutes only a partial component of the consumer price— which also contains further markups along the value chain— the resulting effect on EU domestic human consumption is comparably small.

These EU agricultural policy interventions mainly affect trade. Domestically, the EU fills part of the gap in domestic supply by increased imports and reduced exports to other countries. African imports of meat and dairy products from the EU show a substantial decline. African imports of cereals and oilcakes from the EU increase following the restriction of animal density. This is a consequence of a drop in EU feed demand. The drop in African meat and dairy imports from the EU is mainly compensated by increasing imports from other world regions. A smaller share is offset by additional African production driven by increasing producer prices.

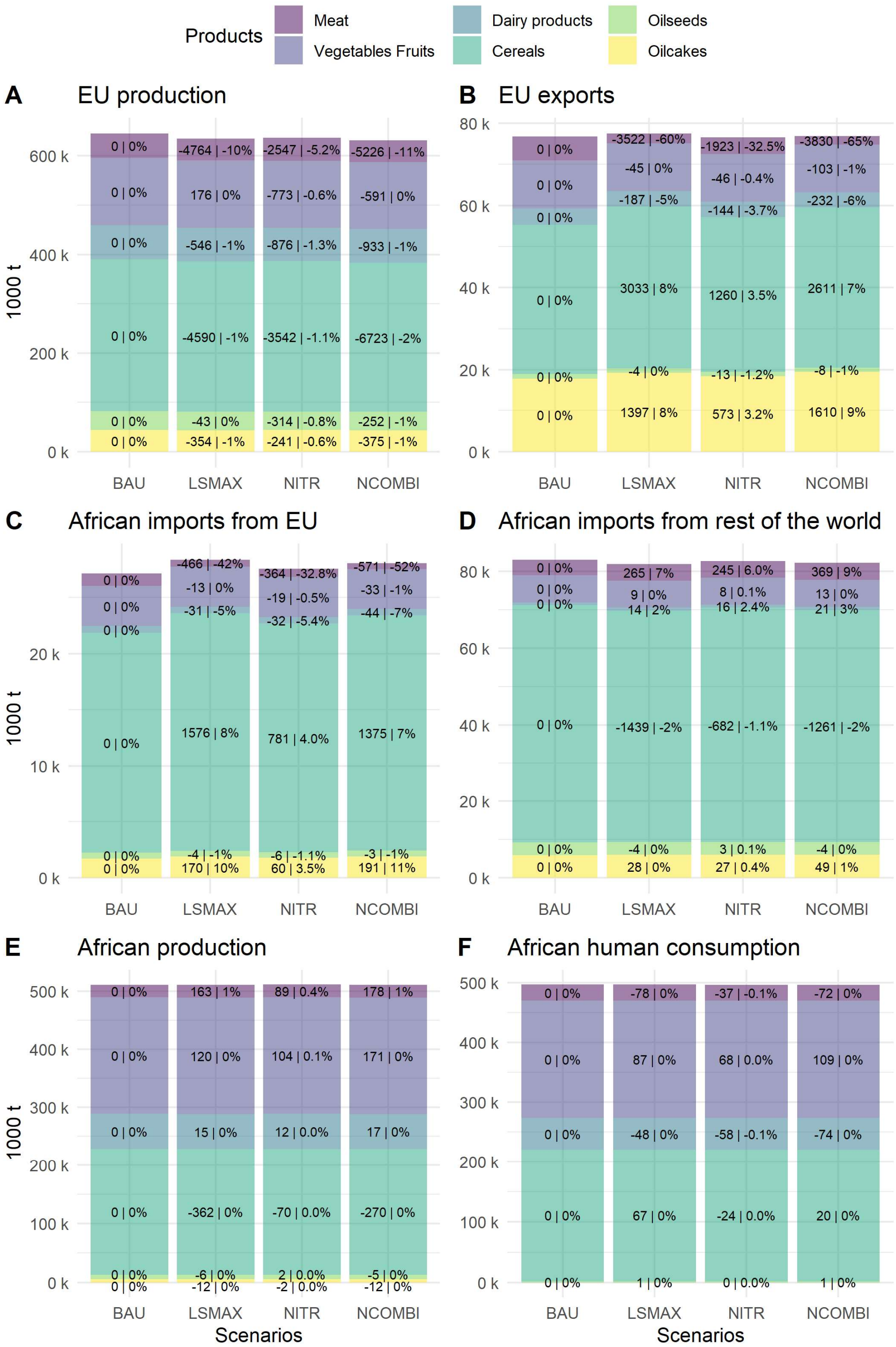

Figure 4.4 Impacts of animal density and nitrogen application restrictions relative to BAU 2030 Note: Volume, absolute and percentage changes for agricultural production (A,E), consumption (F) and trade (B,C,D) for EU and Africa. All products are in primary equivalents, and thus, include processed foods. Source: CAPRI model results.

Table 4.3 Percentage price changes in EU and Africa (Afr) relative to BAU 2030

	Producer price change (%)						Consumer price change (%)					
	LSMAX		**NITR**		**NCOMBI**		**LSMAX**		**NITR**		**NCOMBI**	
	EU	Afr	EU	Afr	EU	Afr	EU	Afr	EU	Afr	EU	Afr
Cereals	-1.7	-0.3	-0.2	0.1	-1.0	-0.1	-0.2	-0.1	-0.0	0.0	-0.1	-0.1
Dairy	4.0	1.0	3.8	0.9	5.5	1.3	3.0	0.6	2.9	0.6	4.1	0.8
Meat	28.2	1.4	11.9	1.0	31.4	1.7	10.6	1.5	4.6	1.1	11.8	1.8
Beef	33.6	1.1	15.4	0.9	37.5	1.4	17.6	1.0	7.9	0.9	19.6	1.3
Pork	46.2	8.7	12.9	3.8	47.5	9.0	14.8	9.1	4.4	4.0	15.1	9.4
Poultry	1.3	0.7	6.6	1.2	5.8	1.3	0.7	0.6	2.8	1.0	2.5	1.1

Source: CAPRI model results

While the situation for African cereal producers deteriorates slightly due to decreased producer prices, income derived from livestock production, especially from pork production, likely increases as a consequence of the rising African producer prices. For African consumers, increased pork prices lead to a reduction of pork consumption by 4 per cent. On African average—and also for the group of African LDCs— energy intake does not seem to be endangered, despite the fact that consumption of some animal products is reduced up to 5 per cent. Nevertheless, for consumers already struggling to access a diverse diet, small price increases could further threaten their food security.

Relative to African production and consumption quantities in the BAU scenario, the respective scenario effects are marginal. While African agricultural profits from livestock production increase, these drop if coming from cereal production. Comparing impacts for the different African regions in CAPRI, cereal imports from the EU are projected to rise in all regions. The strongest increase (7–9 per cent) is implied by the LSMAX scenario. Even though cereal imports also increase if nitrogen application is restricted (NITR), the effect does not appear to be additive if measures are combined (NCOMBI). This is due to the interaction of restrictions on livestock density and nitrogen surpluses. Meat imports from the EU decline strongly in all African regions in all scenarios. Regional effects differ substantially, and the impacts of the combination of nitrogen and livestock density restriction slightly increase further when combined. The strongest percentage decline (up to 94 per cent) is seen for North Africa. However, this is based on a low import level in BAU. In absolute terms meat imports from the EU decrease strongest in the group of African LDCs. The import drop consists largely of reduced pork imports driven by the strongest price change for this product group (Table 4.4).

Table 4.4 Meat imports to African LDCs from the EU (changes relative to BAU 2030)

	Total	**Change**					
	BAU	**LSMAX**		**NITR**		**NCOMBI**	
	1 000 t	1 000 t	%	1 000 t	%	1 000 t	%
Meat	468	-227	-49	-168	-36	-266	-57
Pork	220	-195	-89	-98	-45	-196	-89
Poultry	215	-5	-2	-52	-24	-43	-20
Beef	21	-20	-93	-15	-71	-20	-94
Goat/ Sheep	11	-7	-60	-3	-29	-7	-62

Source: CAPRI model results

Table 4.5 shows the main substituting flows by trading partner or by own domestic production. The regional disaggregation reveals that for most African regions, domestic production is among the most relevant substitution options. The differentiated view reveals that— despite trade relations being diverse among African regions— Brazil and India would play a major role in filling the meat import gap across the continent.

Table 4.5 Substitution of declining African meat imports from the EU (absolute changes relative to BAU 2030)

	Change in 1 000 t								
	LSMAX			NITR			NCOMBI		
	EU	Substitution		EU	Substitution		EU	Substitution	
LDC Africa	- 277	126 **39** 8	Brazil **LDC Africa** India	-168	79 25 **22**	Brazil USA **LDC Africa**	-226	143 **38** 19	Brazil **LDC Africa** USA
North Africa	-23	**15** 2 0,2	**North Africa** India Argentina	-17	**10** 3 0,4	**North Africa** India Argentina	-23	**16** 3 0,3	**North Africa** India Argentina
Morocco	-4	**4** 0,2	**Morocco** Argentina	-7	**5** 0,2	**Morocco** Argentina	-8	**6** 0,3	**Morocco** Argentina
Ethiopia	0	**1**	**Ethiopia**	0	**0,7**	**Ethiopia**	-1	**1**	**Ethiopia**
Nigeria	-8	**4** 0,1	**Nigeria** Turkey	-4	**2** 0,1	**Nigeria** Turkey	-8	**4** 0,1	**Nigeria** Turkey
South Africa	-75	**40** 18 8	**South Africa** Canada Thailand	-63	30 **25** 10	Brazil **South Africa** Argentina	-100	**47** 24 19	**South Africa** Brazil Canada
Rest Africa	- 128	27 26 **17**	Brazil India **Rest Africa**	-104	26 15 15	Brazil USA India	-165	40 29 16	Brazil India Canada

Note: Import substitution of the decline in meat imports from the EU by imports from other regions and African production for serving domestic demand (in bold). Source: CAPRI model results

Compared with adjusting direct payments, implementing restrictions on nitrogen application and animal density shows stronger impacts on EU agricultural trade with Africa. The EU share of African meat imports is reduced by about 50 per cent. Moreover, the relevance of wheat imports from the EU in terms of total African wheat imports increases slightly following the drop in feed demand in the EU. Relative changes in the relevance of imports from the EU are comparable for African LDCs as well as for the non-LDC African countries. However, the share of meat and dairy imports from the EU in the 2030 BAU situation is considerably higher for African LDCs than for the rest of Africa. The observed changes in EU–Africa trade that follow from the adjustments in CAP regulations are predominantly compensated by African trade with other countries. Domestic African production replaces lower imports from the EU only to a limited extent. The comparably low competitiveness of African production systems for the analyzed goods could be a reason for this result.

4.4.3 *Environmental sustainability impacts*

Reducing the total CAP budget in the DP50 scenario implies a small decline in crop production areas within the EU. These areas are largely converted to forestry or other non-agricultural land use. This means a reduction of 2 per cent for the total agricultural area in the EU. In case the budget is transferred instead to Pillar II payments, there is scarcely any change in land-use shares compared with the BAU scenario. The area used for grassland (meadows and pastures) increases slightly as a consequence of the additional support of extensive production and "Less Favoured Area" payments. However, relative to the total area, this change is minor. Nitrogen surpluses at soil level decrease by less than 1 per cent in the DP50 scenario and by approximately 2 per cent with the payment transfer to extensive production. EU agricultural greenhouse gas emissions decrease by about 1 per cent in both scenarios. Globally, agricultural sector emissions show almost no change in relative terms. Overall, environmental improvements related to the simulated changes in direct payments are negligible.

The simulated enforcement of stronger regulations for animal density and nitrogen application hardly changes overall EU agricultural land use. However, some land-use shifts within the EU agricultural area take place at a more disaggregated level. By scenario design, land used for intensive grazing shifts to extensive grazing and the area for voluntary set-aside and fallow land increases with about 14 per cent compared with the BAU scenario. This comes along with a decline in EU average herd sizes by 17 per cent for pigs, 6 per cent for dairy cows, and 4 per cent for male adult cattle if livestock density and nitrogen application restrictions are combined.

Soil nutrient surpluses at the EU level are reduced by about 18 per cent in the NCOMBI scenario relative to the BAU scenario. In those regions with the highest nutrient surpluses in the reference situation, a decrease of up to 88 per cent is found. Total nitrogen surpluses decrease in hotspot areas by

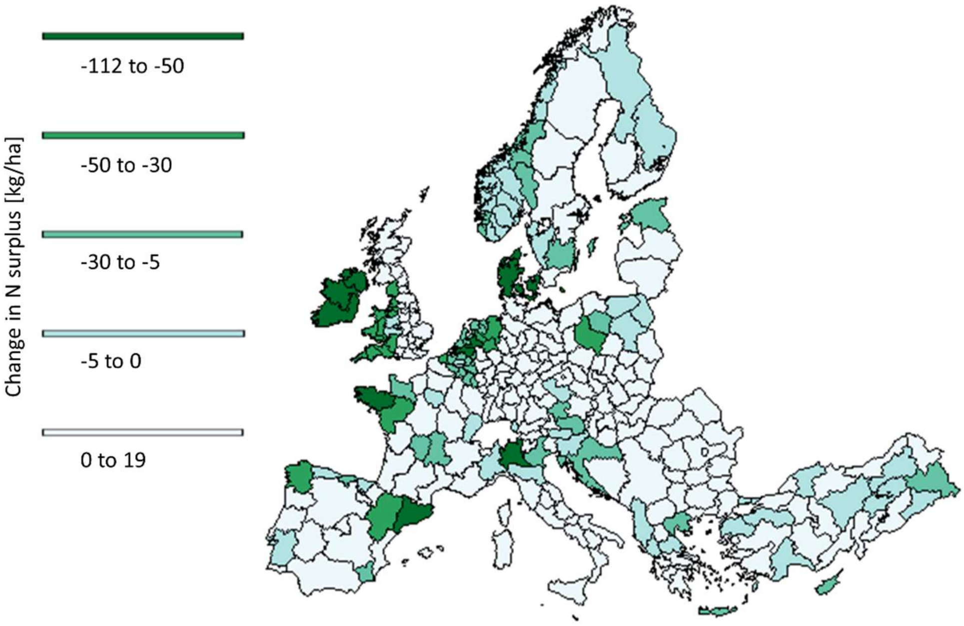

Figure 4.5 Absolute change in nitrogen surpluses in kg N ha^{-1} a^{-1} in the NCOMBI scenario compared to the BAU scenario by NUTS II regions
Source: CAPRI model results.

up to 112 kg N ha^{-1} a^{-1}, while part of the surplus is shifted to other areas that show increases of up to 19 kg N ha^{-1} a^{-1} (Figure 4.5). Greenhouse gas emissions related to the EU agricultural sector decrease by up to 8 per cent in the scenarios that simulate livestock density and nitrogen application restrictions, while global agricultural greenhouse gas emissions vary by less than 1 per cent. Part of the production decrease in the EU is compensated by increased production in other countries, which goes along with emission leakage weakening the actual reduction achievement for the global emission burden (Table 4.6).

Table 4.6 Changes in non-CO2 greenhouse gas emissions related to agricultural production in the EU and in the rest of the world (relative to BAU 2030)

	EU		Rest of the world	
	Mio t CO_2eq	%	Mio t CO_2 eq	%
DP50	-4.1	-1	1.5	0
DPTRANS	-3.4	-1	-0.8	0
LSMAX	-30.7	-6	20.3	0
NITR	-27.4	-6	9.9	0
NCOMBI	-40.0	-8	21.0	0

Source: CAPRI model results

4.5 **Discussion**

Impacts from reducing direct payments EU agricultural production are found to be minimal and largely restricted to marginal land due to the wide decoupling of payments in the past. Existing voluntary coupled support in some member states implies differentiated income effects for farmers as consequence of the cut. The more detailed analysis by Offermann et al. (2016) similarly reveals differentiated impacts by regions and sectors following from a decoupling of direct payments. Increased flexibility regarding the allocation of funds by EU member states is suggested in the CAP reform proposal to reduce bureaucracy and strengthen subsidiarity, but it also raises concerns about preparing the ground for a comeback of the intensified use of voluntary coupled payments (European Commission 2018). These have been criticized for inhibiting agricultural production efficiency in the past (Kornher and von Braun 2020; Matthews 2018; Zhu et al. 2012). A potential return to the increased use of coupled payments could bring back trade distortions eliminated by previous CAP reforms (e.g., Rude 2008). These payments could inhibit innovation and efficiency gains in the agricultural sector (Zhu et al. 2012). A scenario like this could be taken up by future research if such a development occurs.

Assumptions related to the remaining degree of coupling in decoupled agricultural support influence the production and international trade results of our model simulations (Matthews 2018; Urban et al. 2016). Decoupled payments are basically implemented in CAPRI as entirely coupled to the use of agricultural land, because the payment is dependent on keeping the land in a good agricultural and environmental condition. All agricultural land use receives the same payments, apart from voluntary coupled support and payments subject to ceilings. The main effect is an increase in total land demand, while impacts on the crop mix are small. Thus, the remaining influences on land values and farmers' decisions are accounted for in line with impacts related to decoupled payments that are identified in the scientific literature (e.g., Boulanger et al. 2017). However, there are further indirect coupling channels via effects on uncertainties and the risks farmers face, their access to credit, labor allocation choices, or their expectations for the future (Bhaskar and Beghin 2009; Boulanger et al. 2017; Moro and

Sckokai 2013) that are not accounted for in the model. This limitation may lead to an underestimation of the actual impacts that could occur as a consequence of the changes to the CAP payment structure that we have tested.

Besides this, existing CAP measures are represented in CAPRI in great detail (M’barek et al. 2017). Still, the mechanisms used to simulate their impacts cannot cover all in reality possible facets. We refer to a past “Agricultural Outlook” from 2016 (European Commission 2016) for our BAU scenario. This does not account for more recent changes, in particular not for implications related to the 2020 pandemic. The COVID-19 pandemic led to downward corrections for Gross Domestic Product projections. However, the EU economy is expected to recover to pre-COVID levels by 2023 (European Commission 2020b). Furthermore, the pandemic increases uncertainties for international trade of agricultural products. The meat trade has particularly suffered from COVID-19 and African Swine Fever outbreaks (European Commission 2020b). Here, we do not account for the potential longer term economic implications for the agricultural sector that arise from the pandemic. A satisfactory synthesis of the continuously updated information on the post-COVID outlook (e.g., European Commission 2020c) is simply beyond our capacities and the scope of this paper. Still, we expect that the impacts of EU policies on Africa will remain valid in sign and the approximate magnitude after all impacts from the pandemic are correctly factored in because the basic economic mechanisms are assumed to remain in place. There are other limitations to acknowledge, for example, the assumption that economic agents in general adhere to regulations. In terms of nitrogen surpluses, this means that compliance costs (Kuhn et al. 2019) and potentially related non-compliance with regulations are not accounted for. The representations of policy mechanisms, e.g., those related to the Nitrates Directive, are input- or outcome-based. Thus, they do not capture the variety of how actual national action programs and related policy measures are implemented on an EU member state level.

In the applied model setup, the effect of long-term adjustments of primary inputs on supply and trade is reflected only to a limited extent. This could imply an underestimation of trade reactions in the long term, following changes in direct payments. In contrast, the restrictions on animal density and nitrogen application will likely induce the implementation of technologies that use fertilizer more efficiently in the long term. This might compensate for some of the projected production and trade impacts. Even though our modelling results are influenced by the assumptions that underly the model implementation, our general results are supported by the scientific literature that similarly concludes that the impact of CAP payments on trade is limited (Matthews et al. 2017). Also, Boulanger et al. (2018) show the limited influence of the CAP on agricultural production in Sub-Saharan Africa and suggest increased support aimed at productivity gains in and trade involvement of the African agricultural sector.

Price changes in EU trading partner countries as consequences of new CAP measures will probably affect net food consumers and producers in opposing directions (Matthews 2018). While production and consumption in African countries remain unaffected by changes related to EU CAP direct payments, enforcing livestock density and nitrogen application restrictions in the EU impacts prices for animal products in African countries. On average, especially pork prices could change and lead to increased production and reduced human consumption in Africa. As a consequence, dietary diversity could be at risk for net consumers if animal products become less affordable. This could aggravate food insecurity incidents for net food consumers and place SDG2 to end hunger (UN 2015) further out of reach. However, African producers could increase competitiveness beyond what is suggested by the underlying trend projections and this could ease suggested impacts on welfare and food security of African producers and consumers. Assessing the welfare implications for each African country individually— or even at subnational level— is, however, beyond the scope of this study.

4.6 Conclusion

The future of the EU's CAP is subject to international commitments on climate, environmental, and sustainable development goals. Our analysis indicates that the implementation of stronger regulations on extensification, animal density and nitrogen application in the EU imply limited consequences for production and consumption in African trading partner countries. Nevertheless, in contrast to changes in direct payments, restricting animal density and nitrogen application in the EU has substantial implications for the trade flows between the EU and African countries with respect to certain agricultural products. EU meat production declines of up to 11 per cent in the combined scenario impose a reduction of more than 50 per cent of African meat imports from the EU. Implied social and economic consequences for EU farmers and a potential further concentration in the EU agricultural sector are beyond the focus of the study at hand.

Directing the future CAP more strongly toward environmental sustainability can potentially increase production in non-EU regions, including low-income countries. Our assessment shows that substituting domestic production and trade flows are likely to fill the gap in African regions caused by EU production decreases due to the assessed agricultural policy reforms. To what extent these potentials can be used by producers in African regions depends at least partly on their competitiveness compared with substituting importers and on the access their products have to export markets (Matthews 2018). Therefore, investments in Africa's agricultural sector intended to specifically improve agricultural productivity and the functioning of agricultural value chains are inevitable to promote agricultural growth in Africa and international trade between Africa and the EU (Kornher and von Braun 2020; Task Force Rural Africa 2019).

In general, international trade bears a welfare increasing potential through lower prices for food or production inputs and through additional opportunities for sales to export markets. In our scenario assessment this is exemplified by increased consumer prices as consequence of reduced trade flows for animal products followed by potential implications for poor net-food consumers. However, the 2020 global economic downturn as consequence of the Corona virus pandemic reveals several risks incorporated in the interconnectedness of global value chains. Scarcity following production stops and border closings endanger the functionality of food supply chains and the access of import-dependent countries (Coke Hamilton and Nkurunziza 2020; FAO 2020; Gauber et al. 2020). These observations stress the necessity to develop crisis prevention strategies that may also involve measures that support domestic production of some critical products. The consequences of climate change may also make the occurrence of similar economic events more likely in the future (Dellink et al. 2017).

Trade-offs regarding global SDGs are inherent in the analyzed, regionally implemented agricultural policy changes. By scenario design, environmental improvements at the EU level and in hotspot regions for nitrogen surpluses are achieved. In order to reach environmental improvements also at global level, additional measures are required to minimize leakage effects and improve environmental sustainability beyond the European context. Complementary measures could be implemented to induce a demand reduction in high-income economies like the EU, which would support reaching the environmental targets on a global scale (Latka et al. 2021). Reducing demand and supply of emission-intensive products jointly could contribute to environmental sustainability. However, this might limit potential trade opportunities with the EU that could improve social and economic sustainability in low- and middle-income countries, also in Africa.

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Data availability

The data underlying this article are available in the article and in its online supplementary material. The model CAPRI is available at https://www.capri-model.org/. More information on the version of the model used and on the results files are available from the corresponding author on reasonable request.

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4.8 Appendix

4.8.1 *A. Regional classification*

Table 4.7 List of CAPRI regions and region aggregates used in this study

CAPRI regions/ region aggregates	Note
Ethiopia	
Morocco	
Nigeria	
South Africa	
North Africa*	Northern Africa without Morocco
LDC Africa	Angola, Benin, Burkina Faso, Central African Republic, Chad, Djibouti, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauretania, Mozambique, Niger, Ruanda, Senegal, Sierra Leone, Sudan, Tanzania, Togo, Uganda, Zambia
Rest Africa	Botswana, Côte d'Ivoire, Ghana, Cameroon, Cap Verde, Kenia, Mauritius, Namibia, Swaziland, Zimbabwe
Africa	Aggregate of the above
Northern Africa	North Africa and Morocco
Sub-Saharan Africa (SSA)	Africa without Northern Africa
EU	In data and analysis assessed on EU aggregate level (the model contains much more detail at EU level not in the main focus of the study at hand)
Argentina	
Brazil	
Canada	
India	
Thailand	
Turkey	
USA	
Asia	Asian countries (including India and Thailand)
Middle- and South America	Middle- and South American countries (including Argentina and Brazil)
Middle East	Countries located in the Middle East
Oceania	Australia and New Zealand
Rest of Europe	Non-EU European country aggregate
Rest of World	World without EU and African countries

Note: Countries except for African countries are listed explicitly, if these were the main trading partners of African regions found to increase exports after a decline of exports from the EU based on the regional detail covered by CAPRI. *North Africa includes Algeria, Egypt, Tunisia and Israel given the way the database composes these as group of Mediterranean countries.

Table 4.8 List of CAPRI sectors used in this study

CAPRI sector used in this study	Note
Beef	
Pork	
Poultry	
Goat and sheep meat (Goat/Sheep)	
Meat	Beef, Pork, Poultry, Goat/Sheep meat aggregate
Dairy	Dairy products including among others fresh milk, butter, cheese, milk powders
Cereals	Barley, maize, oats, rye, meslin, wheat, other cereals
Vegetables and fruits (VegFruit)	Aggregate of vegetables and fruits
Oilcakes	Soy cake, sunflower cake, rapeseed cake
Oilseeds	Soya, sunflower seeds, rapeseeds
Coffee, cocoa and tea (CofTea)	Coffee, tea, cocoa aggregate
Other	all agricultural products not captured under the explicit groups including fish, sugar, oils, eggs, rice, pulses, potatoes

Table 4.9 Livestock densities in the BAU and LSMAX scenario across EU regions

Scenarios	**BAU**			**LSMAX**		
Production Activities	**Beef**	**Dairy**	**Other animals**	**Beef**	**Dairy**	**Other animals**
Average	0.11	0.29	0.34	0.09	0.25	0.23
Maximum	0.73	2.39	7.52	1.13	1.5	1.5
Average change compared to BAU				-0.02	-0.04	-0.11
Maximum reduction compared to BAU				-0.60	-2.0	-6.55

Note: Livestock density is calculated by dividing animal numbers by the available utilized agricultural area for each NUTS II region. The table shows average and maximum densities across NUTS II regions as well as the average change and the maximum reduction across NUTS II regions in the LSMAX scenario compared to the BAU scenario. Source: CAPRI model results

4.8.2 *B. Self-sufficiency*

Table 4.10 African domestic supply, domestic demand, and self-sufficiency shares in BAU 2030

Product group	Domestic supply (Mio t)	Domestic demand (Mio t)	Self-sufficiency share
Meat	22	27	0.81
Vegetables/ Fruits	20	21	0.97
Dairy	60	61	0.99
Cereals	215	286	0.75
Oilseeds	7	11	0.66
Coffee/ Tea/ Cocoa	5	2	2.09
Oilcakes	6	13	0.43

Source: CAPRI model results

4.8.3 *C. Supplementary data*

Supplementary data to this article is provided in the online supplementary material under https://doi.org/10.1093/qopen/qoab003.

Chapter 5
Effects of food price volatility on children's nutrition in sub-Saharan Africa[§]

Abstract: Food access can be strongly buffeted by high and volatile food prices. Price volatility transmits from international prices and can be caused by climate shocks, but evidence for subnational markets is scarce. Here, we decompose local price volatility across local markets in 24 sub-Saharan African (SSA) countries to understand the sources of variation using econometric and machine-learning approaches. We strip out expected seasonal price volatility to isolate the effect of unexpected volatility. Our decomposition suggests that local price volatility is strongly driven by volatility in global futures prices. While high prices can clearly affect food affordability, the role of price volatility on food security is less definite. In this study, we use DHS data on 329,676 children over 19 years to measure how food price volatility affects children's nutrition in SSA. To identify the relevant timing, we compare nutrition effects of price volatility in the preceding year and around the time of a child's birth. The effect of price volatility on children's nutrition can be subject to endogeneity since local production shocks and policies can affect both, nutrition and prices. Also, household decisions to buy or sell on the local market can be determined by

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Credit: Catharina Latka: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. Kathy Baylis: Conceptualization, Methodology, Writing – review & editing, Supervision. Tess Lallement: Resources. Thomas Heckelei: Conceptualization, Methodology, Writing – review & editing, Supervision.

their children's nutrition and thus simultaneously affect local food prices. We use global price volatility and, in some models, local weather shocks to instrument for local price volatility and address this potential endogeneity concern. We analyze the effect for six nutrition indicators using multi-regression analysis and compare our instrumented mean unexpected price volatility with other price volatility indicators. We distinguish household subgroups (poor vs rich, rural vs urban, agricultural vs non-agricultural) to account for heterogeneity in the resulting effects. Our results indicate that unexpected nonseasonal price volatility increases the occurrence of stunting in children and decreases the underlying height-for-age z-score. The impacts on stunting are especially large and significant for rural, agricultural and poor households. Predicted mean unexpected volatility reduces diet diversity, most significantly and strongly for children below 2 years of age. However, we do not find similarly robust effects for all nutrition indicators.

Keywords: stunting, diet diversity, price volatility, weather shocks, econometrics, machine learning, Shapley values

5.1 Introduction

High and volatile food prices affect many households' access to food in sub-Saharan Africa (SSA), especially when food comprises a large fraction of household expenditure (Drammeh et al., 2019). If food access is reduced, food and nutrition insecurity can follow, lowering diet diversity, and leading to long-term consequences for health, developmental, and economic outcomes (Currie and Vogl, 2013; Engle et al., 2007; Hoddinott et al., 2013; Moradi et al., 2019). Despite the United Nations' Sustainable Development Goal 2 (UN, 2015), which aims to end all forms of malnutrition by 2030 while reducing stunting and wasting in children under 5 years of age by 2025, little progress has been achieved in SSA countries (Pomati and Nandy, 2020). Furthermore, child malnutrition prevails, especially in East and West Africa (Akombi et al., 2017). The global COVID-19 pandemic is expected to worsen this situation as it has induced rising staple food prices in SSA (Agyei et al., 2021; Laborde et al., 2021). Shortfalls in wheat production as a consequence of the fighting in Ukraine in 2022 have already restricted global staple food supplies. The effects of high and volatile food prices on food security and malnutrition among children must be better understood, particularly how food price movements are related to different nutrition outcomes. Nonseasonal price volatility might especially be a threat to children's nutrition, as households are affected rather unexpectedly (Amolegbe et al., 2021).

Food prices depend on supply and demand in a functioning market and may vary by season, agri-food policies, weather shocks, and macroeconomic impacts, including those driven by agricultural futures markets and spillovers from related sectors, such as bioenergy and land (Amolegbe et al., 2021; Cornia et al., 2016; Gilbert, 2010). High staple food price levels are expected to prevail as a phenomenon in several African countries in the coming decades because of demand increases, local production shortfalls, and limited imports (Zhou and Staatz, 2016). Price shocks affect food consumption in the short-term via two main direct channels: real income effect and substitution effects (Kalkuhl et al., 2013). Increased spending on high-priced staple foods can reduce a household's available budget for other foods, thus affecting dietary diversity (Dorward, 2012). Insufficient food and caloric supply can cause malnutrition, which leads to stunting, wasting, and underweight afflictions. Moreover, a dietary focus on staple, energy-dense foods can lead to overweight conditions, thus creating a double burden of malnutrition: the simultaneous prevalence of overweight and underweight conditions in the same region. This phenomenon has been increasingly observed in urban SSA regions (Jones et al., 2016). Food price changes can furthermore indirectly affect nutrition since a decrease of real income might reduce available budget for healthcare or increase working hours correlated which reduced time for breastfeeding and childcare (Kalkuhl et al., 2013).

Estimating the effect of price volatility on nutrition is complicated by the potential for endogeneity. Factors that might affect price volatility, such as local production shocks and domestic policies might affect nutritional outcomes, also through routes other than food prices. For example, a trade ban as reaction to a drought event can affect nutrition not only through price changes but also through employment effects. Also, household decisions to buy or sell on the local market can be determined by their children's nutrition and thus simultaneously affect local food prices. We control for local weather shocks and use global price volatility to instrument for local price volatility and address this potential endogeneity concern. Both instruments are supposed to explain variation in local price volatility, but are assumed to not be affected by local market prices, demand, supply, or nutrition themselves. Since weather can affect nutrition also through other channels than the price, we additionally control for the weather variables in some model specifications of the nutrition-price analysis. However, in these cases, weather cannot be regarded as a pure instrumental variable.

In this paper, we ask two related questions. First, what is the source of unexpected maize price volatility in SSA? Second, how does this price volatility affect children's nutrition. We begin by decomposing local food price volatility in SSA into variation driven by global corn futures and local weather shocks. In addition to a fixed-effects econometric approach, we pursue machine-learning (ML) for decomposing price volatility without pre-imposed restrictions related to the functional form. Furthermore, we examine how local food price volatility affects nutrition outcomes for children under 5 years of age. Therefore, we compare six nutrition indicators (i.e., stunting, underweight, overweight, their underlying anthropometric z-scores, and dietary diversity). We assess food price volatility during the year before the nutrition measurement and during the years before and after a child's birth. Furthermore, we control for a series of additional variables representing child-, parent-, household-, and market-specific characteristics.

Our work contributes to two separate strands of literature. First, we complement existing research on the causes of local food price volatility. Here, we focus on the contributions of weather shocks and international price volatility. Second, we contribute an extensive cross-country analysis of local price volatility impacts on children's nutrition.

Weather and climate notably affect food prices through their effects on crop yield and market food supply (Brown and Kshirsagar, 2015; Mirzabaev and Tsegai, 2012). Prior to their effect on actual food production, weather shocks affect expectations of price changes, causing buying behavior to change and leading to price fluctuations in local markets (Letta et al., 2022). Crops differ in their sensitivity to weather changes and farmers may adjust their cropland decisions in response to weather shocks (Haile et al., 2017; Salazar-Espinoza et al., 2015). Cross-price effects and substitution behaviors can transfer weather effects from one commodity to production, demand, and prices of others; for example, weather affecting the production of wheat will also affect prices of maize, or livestock. Local weather shock implications on food prices can be mediated by product tradability and storability (Mirzabaev and Tsegai, 2012).

In times of increasingly globalized value chains, international food price movements trickle down to local markets. Import and export trade flows steer local market food supplies, depending on their global market integration and moderate local weather shocks. Moreover, changes in global futures prices can be transmitted by changing price expectations to local levels (Letta et al., 2022). The transmission of food price shocks from the global level to the consumer level is found to be considerably stronger in low-income countries (Bekkers et al., 2017). Price spikes are more likely passed on whereas this is found to be rarely the case for price drops (Ianchovichina et al., 2014).

Price transmission is often studied on the basis of balanced time-series or panel data using vector autoregressive models (e.g., Ianchovichina et al., 2014). For the current study, we do not follow this approach, given that our data are very unbalanced. We contribute to the existing literature by assessing and decomposing food price volatility at local market levels in SSA, where food access is a fundamental concern for many households. We deviate from typical price transmission estimations, as we do not use continuous data of price changes and their lags, but regress rolling local mean price volatility on futures volatility, also controlling for weather shocks and market fixed effects. Furthermore, we use a single market's price instead of a food price index. In our analysis, we do not control for trade integration or trade policies. We use a two-fold price volatility decomposition approach, comparing econometric regressions with ML decomposition. We achieve a convincing model fit for a gradient boosted tree with an R^2 in the training set of 0.82 and in the test set of 0.80. Both approaches stress a strong positive correlation between unexpected futures volatility and unexpected local market price volatility, whereas the direction of implications from rainfall and temperature appears to be more heterogeneous.

Extant studies that assess the impact of food prices on the nutrition of children in SSA typically focus on one price measure and rarely provide inter-country comparisons. While limited, the evidence is suggestive. Arndt et al. (2016), for example, show that high food price inflation increases wasting and underweight conditions among children in Mozambique. Amolegbe et al. (2021) assess the impact of rice price volatility on diet diversity and food expenditure shares for Nigeria. Grace, Brown and McNally (2014) conclude that increasing maize prices before pregnancy correlate with low birth weights in Kenya. For Malawi and Niger, Cornia et al. (2016) show that the trend, seasonal, and famine components of food prices significantly affect child admissions to feeding centers.

In this paper, we add to the existing research by analyzing local market price data for maize in 24 SSA countries to compose and compare multiple price volatility indicators (i.e., (unexpected) volatility, drops, and spikes) for different time lags), and estimate their effect on a range of nutrition indicators. The prevalence of stunting is found to be generally larger than that of wasting and underweight conditions, especially in Africa (Ssentongo et al., 2021). Stunting is often referred to as chronic malnutrition. Underlying biological mechanisms appear quite complex, which stresses the need to address different forms of malnutrition (Briend, 2019). We use nutrition indicators provided by Demographic Health Survey (DHS) data on 329,676 children over 19 years and 24 SSA countries. We make use of the variation in our data over time and space and disentangle the effects on different household types, to better understand the heterogeneity of findings for rural vs. urban, rich vs. poor, and agricultural vs. non-agricultural family types. We explore the effect of weather shocks as a potential mechanism to understand whether these drive both, prices and nutritional outcomes, directly. We also address potential simultaneity issues related to the relation between staple food prices, market quantities and nutrition by using an instrumental variable approach in our model.

In Section 5.2, we present the conceptual framework of market price effects on children's nutrition. The research data, including descriptive statistics and methods, are described in Section 5.3. The results of price decomposition and the nutrition–price analyses are presented in Section 5.4 and discussed in Section 5.5, whereafter concluding remarks are provided in Section 5.6.

5.2 Conceptual framework

Market food prices are expected to mainly affect children's nutrition through their impact on a household's food access. As visualized in Figure 5.1, there are many underlying linkages to be considered. Causes for changes in local market food prices can arise from a local production shock, e.g., due to weather extremes, or as a spill-over from international market price changes. For example, a resulting shortage in local market food supply can increase local food prices. This may negatively affect market food demand. Food access deteriorates, reduced food purchases and intake can worsen children's nutrition. This effect can be moderated by food substitution, if only the market for a certain food is affected.

It remains difficult to determine whether food price impacts on children's nutrition are driven by actual price movements or primarily by reduced food availability per se. Moreover, children's nutrition might simultaneously affect household decisions regarding food production, storage, purchases, and subsistence. Through food supply and demand, nutrition and food prices could therefore influence each other. We address this problem by using an instrumental variable approach based on (i) international market prices and (ii) weather shocks, both unlikely to be affected by local food supply and demand but supposedly correlated with local food prices. The first stage price volatility decomposition allows to better identify the impact of local food price movements on children's nutrition in the second stage. Moreover, an econometric model that includes both, food market prices and quantities, might cause identification issues. Therefore, and owing to limited data availability, we do not include local production quantities in our model.

In addition, weather shocks do not only affect children's nutrition through their impact on food availability and access. There can also be a link through direct health effects caused by heat stress, disease spreading, or clean water scarcity that influences children's nutrient uptake and parents' productivity and income opportunities (Brown et al., 2014; Cooper et al., 2019; Gebre and Rahut, 2021; Grace et al., 2021; McMahon and Gray, 2021; Nawrotzki et al., 2016). We account for these other channels of weather on nutrition by controlling for total rainfall and mean temperature in some of our model specifications. However, in these cases, weather shocks cannot be regarded as instrumental variable.

Extreme weather events might also encourage the implementation of protectionist or other domestic policies that affect children's nutrition through other channels than the price. For example, trade bans can reduce employment opportunities of parents and affect children's nutrition through policy-induced income effects. Food aid on the other hand might improve nutrition and thus counteract the expected price shock. Such policy implications would occur concurrently to the price adjustments and might be endogenous to our resulting price volatility effects. By using futures volatility to instrument local market price volatility we address this endogeneity concern.

We are aware that there are further confounding factors related to geographic characteristics of market and household locations that affect both, nutrition and market food supply. These include local institutional settings, policies, market integration and access, infrastructure, sanitation facilities, and the regional climate settings. By using market-fixed effects we account for such time-invariant local variation in our analysis. Complementarily, years with wide-spread nutrition shocks, e.g., caused by a global heat wave, are controlled for with year-fixed effects.

Changes in staple food prices are of great relevance, since staple foods comprise a large share of diets especially of food insecure children, they are required to cover the minimum caloric intake, and therefore other dietary components may be sacrificed for their consumption. Implications for different household subgroups, identified by household and parent characteristics, are likely heterogenous.

Staple food price volatility likely affects food access, which, in turn, affects children's nutritional outcomes differently for net producing and purchasing households. High food price levels can reduce net food buyers' access to food , unless incomes adjust accordingly, whereas net food sellers might benefit from positive income effects (Kalkuhl et al., 2016; Wodon and Zaman, 2010). Volatile prices can cause fluctuating food access with alternating periods of easy and difficult access for households with credit constraints, while wealthier households may have the option of building stocks in times of low prices. Staple food price volatility increases the risk and transaction costs for producers, discouraging investments in efficient staple production systems, while urging food-deficit agricultural households to maintain the production of staples instead of diversifying their crop choices (Poulton et al., 2006). Some part of volatility is reoccurring, such as generally higher prices during lean season (Maître d'Hôtel and Le Cotty, 2018), and is thus predictable by households and producers. If it is within their means, producers and households stock food as a coping strategy. The unexpected part of volatility, on the other hand, may drive additional risk to food security that is more difficult to foresee.

Unexpected volatility may come in the form of price spikes. Sudden and severe price increases restrict food access of net-buying poor households that lack the ability to build stocks. Price drops might, on the other hand, generate a sharp fall in producers' income. The corresponding households may adjust their food storage and selling behavior prioritizing their own subsistence consumption, which can result in giving up the highest retrievable profits and increasing price volatility further (Maître d'Hôtel and Le Cotty, 2018). Overall, children's nutrition in households that rely on purchased foods might benefit from price drops and suffer from price spikes, whereas the opposite might hold if the household's income is strongly connected to food prices on the market. The latter though will not hold if price changes result from the local households' production quantity. For example, producing households only benefit from high prices if they have the capacities to supply the market – this effect is of course limited if their own production shortfall was the underlying reason for the price increase.

Whether food access and nutrition are protected from price movements depends on the interplay of household assets, household income, parent and children characteristics. Wealthier households spend a smaller share of their income on food and are more likely able to increase their food budget to mitigate food price increases. Higher parent education can be a sign of more profound nutritional knowledge, which might result in better childhood nutrition, although impacts of parental education on stunting are found to be modest (Alderman and Headey, 2017). Having agricultural assets can be seen as an additional source of wealth. Households with agricultural assets or female occupations in agriculture may obtain income from agricultural activities and have additional means with which they can ensure subsistence. In the former case, such households might benefit from increased agricultural prices when they sell their products. However, they might also suffer from increased input costs (e.g., for animal feed). In the case of subsistence production, farming households might be hardly affected at all. Rural and urban households might be affected differently, as rural households might fall back on subsistence production, while urban households may be more reliant on food purchases. Rural markets are potentially less integrated and may be less strongly affected by international price transmissions. In contrast, improved access to food imports can enhance the nutrition of children in urban households as trade can be used to balance the effects of local weather shocks. We account for this with market fixed-effects.

Children's characteristics can also determine nutrition outcomes (Buisman et al., 2019). Different shocks to food availability are likely to have differing effects depending on the child's developmental stage. For example, older children who are no longer breastfed might be more directly affected by reduced staple food access. Mothers might buffer especially younger children's caloric intake by reducing their own consumption (Block et al., 2004). Nutrient needs of mothers and infant children are especially high during pregnancy and the following two years, but can only be met with sufficiently diverse diets (Adu-Afarwuah et al., 2017; Dewey, 2013). If a child has a higher birth order or is born as a twin, the household food is shared with more people. A child's sex might also influence how food

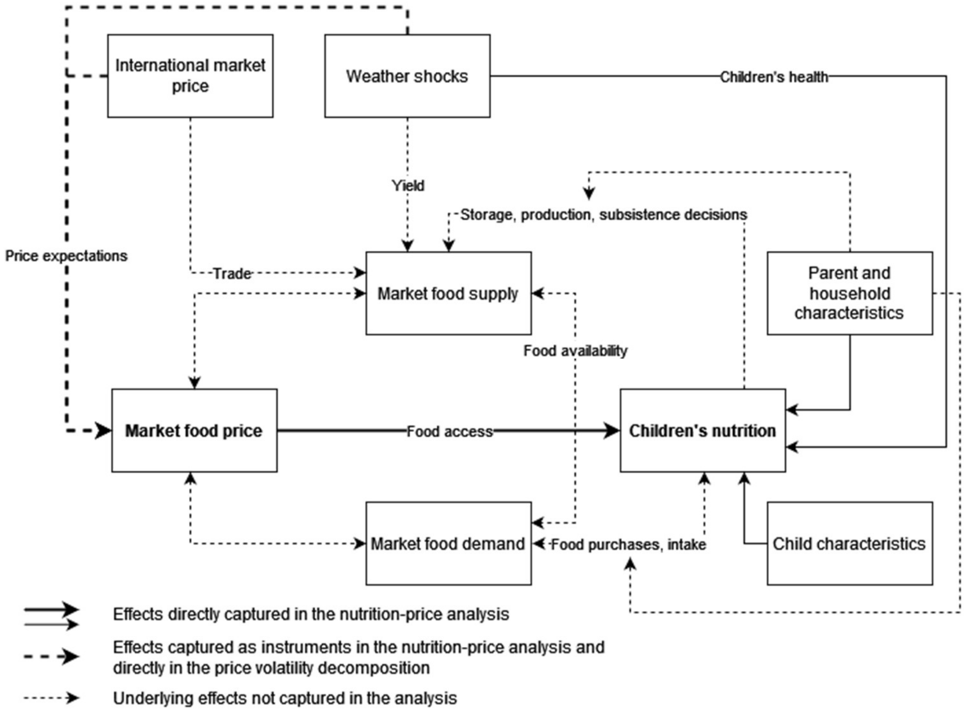

Figure 5.1 Conceptual framework of market price effects on children's nutrition

availability affects nutrition for biological and especially for cultural reasons (Keino et al., 2014; Wamani et al., 2007).

5.3 Research data and methodology

5.3.1 *Price decomposition*

We employ monthly maize price data consolidated from the Global Information and Early Warning System on Food and Agriculture (GIEWS)[7], the World Food Program (WFP)[8], and the Famine Early Warning Systems Network (FEWS)[9] for 603 local markets across all investigated SSA countries and matched survey years (Table 5.1). For each market we determine the dominant maize price based on the longest data series

[7] https://fpma.apps.fao.org/giews/food-prices/tool/public/#/home
[8] https://data.humdata.org/dataset/wfp-food-prices
[9] https://fews.net/fews-data/337

available among the different sources. Rolling mean prices for each market serve as price levels $\overline{P_{m,t}}$ varying by market m, and point in time at month t. We compose a general price volatility measure $V_{m,t}^{gen}$ following Kornher and Kalkuhl (2013) based on the standard deviation of the difference of logarithmic monthly price changes over the preceding twelve months.

$$V_{m,t}^{gen} = \sigma_{m,t} = \sqrt{\frac{\sum_{t-11}^{t}\left(\log \Delta p_{mt} - \overline{\log \Delta p_m}\right)^2}{N-1}}$$

Our main price variable of interest is the mean unexpected non-seasonal market price volatility. In contrast to price trends or seasonally reoccurring price movements, unexpected price volatility is presumably the most difficult for a household to prepare for. To compute the unexpected nonseasonal price volatility $V_{m,t,s}^{unexp}$ for each market m and at a certain point in time t, we closely follow the approach described by Amolegbe et al. (2021). We however deviate by using non-deflated prices that have been converted to USD based on available exchange rates to compute price variables in a comparable unit across markets and countries. In addition, we include the month after harvest H_m as dummy before detrending the prices.

We regress the price against a continuous time variable C and include a month-after-harvest dummy H_m

$$P_{m,t,s} = \alpha_m + C_{t,s}\beta_m + H_m + \varepsilon_{m,t,s}$$

and calculate the detrended price

$$P_{m,t,s}^{det} = P_{m,t,s} - \widehat{P_{m,t,s}}$$

Then, we calculate the unexpected nonseasonal price volatility as the difference between the deflated, detrended price and its market- and season-specific average:

$$V_{m,t,s}^{unexp} = P_{m,t,s}^{det} - \overline{P_{m,s}^{det}}$$

As the main variable of interest we use the rolling 12-months average of this unexpected price volatility

$$\overline{V_{m,t,s}^{unexp}} = \frac{\sum_{t-11}^{t}\left(V_{m,t,s}^{unexp}\right)}{N}.$$

We test this measure of volatility against the rolling 12-months average of the positive $V_{m,t,s}^{+\,unexp}$ and negative $V_{m,t,s}^{-\,unexp}$ unexpected volatility following the definition of unexpected price drops and spikes in Maître d'Hôtel and Le Cotty (2018).

$$\overline{V_{m,t,s}^{+\,unexp}} = \frac{\sum_{t-11}^{t}\left(V_{m,t,s}^{+\,unexp}\right)}{N}$$

We calculate price drops analogously, but use the absolute values $|\overline{V_{m,t,s}^{-\,unexp}}|$ to facilitate interpretation of resulting effects. Before assessing the effects of price volatility on children's nutrition, we like to understand how much of it comes from local versus global shocks. Therefore, we decompose price volatility to assess how much it is driven by the corresponding nonseasonal futures volatility, capturing global price movements, and – in lieu of missing yield data – local weather shocks. We conduct this same decomposition on price levels, general volatility and non-averaged unexpected volatility as comparisons.

To create market-specific agriculturally-relevant weather data, we identify nearby maize-growing regions and extract temperature and precipitation during the relevant prior crop growing season. Nearby maize-growing regions are identified based on production quantity raster data from FAO's Global Agro-Ecological Zones (GAEZ) available from International Institute for Applied Systems Analysis (IIASA)[10]. Within each maize-growing region random points are drawn for which weather information is collected. Daily rainfall data is retrieved from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (Funk et al., 2015). Mean monthly temperature data are taken from the National Centers for Environmental Information (NCEI)'s Global Historical Climatology Network (GHCN)[11].

To capture the international market price for maize, we use daily CBOT nearby corn futures prices (closing price) between 1990 and 2019[12]. We

[10] https://iiasa.ac.at/models-and-data/global-agro-ecological-zones

[11] https://www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-monthly

[12] CME Group. (2019). CBOT corn futures contract prices (Daily data, Sep 2009–Oct 2019). https://bba.bloomberg.net

aggregate these to monthly average prices. General futures volatility and unexpected futures volatility are constructed analogously to the market price indicators.

For the decomposition exercise, we estimate linear regressions without and with controlling for fixed effects for markets, years, and months (Eq. I) for mean unexpected price volatility. Comparisons of the full fixed effects models for price levels, general volatility and unexpected price volatility can be found in the Appendix. The analogous futures indicators, the weather variables, and (optionally) interaction terms of the futures indicator and the weather variables, are included as explanatory variables. Eq. I is also the first stage of our two-stages instrumental variable approach that we obtain from the decomposition exercise.

$$\overline{V_{m,t,s}^{unexp}} = \omega R_{m,r} + \theta T_{m,r} + \gamma \overline{F_{t,s}^{unexp}} + \rho R_{m,r} \overline{F_{t,s}^{unexp}} + \tau T_{m,r} \overline{F_{t,s}^{unexp}} + Y_t + S_s + M_m + \varepsilon_{m,t,s} \quad \text{(I)}$$

$with\ R_{m,r} = total\ rainfall\ in\ previous\ crop\ season\ (r)\ nearby\ a\ market\ (m),$

$T_{m,r} = mean\ temperature\ in\ previous\ crop\ season\ (r)\ nearby\ a\ market\ (m),$

$Y_c = year, M_m = market, S_s = month$

To allow for greater flexibility in the model specification, we also use ML to decompose our main variable of interest: the mean unexpected price volatility. ML approaches are data-driven and able to capture non-linearities without imposing a functional form (Storm et al., 2020).

We compare different ML techniques with a focus on gradient-boosted trees which are found to perform with great accuracy (Yoon, 2021). We primarily use CatBoostRegressor[13], which directly includes categorical variables. We also conduct a Shapley value decomposition based on Python's SHAP package [14]. Shapley values indicate the relation between a feature (explanatory variable) value and how it affects prediction of the dependent variable. Shapley value decomposition is used in different research contexts to disentangle features' influences (Li and Zhang, 2021) and for its appreciated properties (e.g., of handling zero values (Balezentis et al.,

[13] https://catboost.ai/en/docs/concepts/python-reference_catboostregressor
[14] https://christophm.github.io/interpretable-ml-book/shap.html

2022)). We compare the resulting Shapley value decomposition to other ML models in the Appendix. Model validation is ensured by randomly dividing the dataset in a test and training set.

5.3.2 *Nutrition–price analysis*

To assess children's food security and nutrition, we use DHS[15] data, which are nationally representative. In the dataset, each child is observed once but not over time. We calculate the diet diversity score using the method of Niles et al. (2021). For stunting, we use the height-for-age z-score (haz), and underweight and overweight are calculated using the weight-for-age z-score (waz)[16]. For the binary indicators we refer to a two standard deviations threshold below the mean on the WHO Child Growth Standards implying moderate or severe nutritional deficiencies. Our data cover 24 SSA countries and survey rounds between 1998 and 2020. Food security and price data are matched on the basis of geo-locations of surveyed households and markets[17]. The number of available markets in our dataset varies between 1 and 75 markets per country. For countries with fewer markets in the dataset, distances between households and their matched markets can get long. We control for the matching distance in our estimations. Additionally, we create further matchings between households and lagged market prices since we include price indicators related to the 12 months before and after the child's birth and allow for this being different markets in case price data from closer markets is available around the birth time. For example, a household is assumed to face the price of the nearest market in the year prior to the survey. If no prices are available for this market in the year of the child's birth, the closest market for that time period is used. Household characteristics such as wealth, assets, or location, and parent characteristics like education and occupation determine how volatile and high food prices influence the food

[15] https://dhsprogram.com/Methodology/Survey-Types/DHS.cfm

[16] https://dhsprogram.com/data/Guide-to-DHS-Statistics/Nutritional_Status.htm

[17] Matching in R based on distm and distHarversine, market with minimum distance to a household chosen among markets within a respective country for which price data are available for relevant matching years

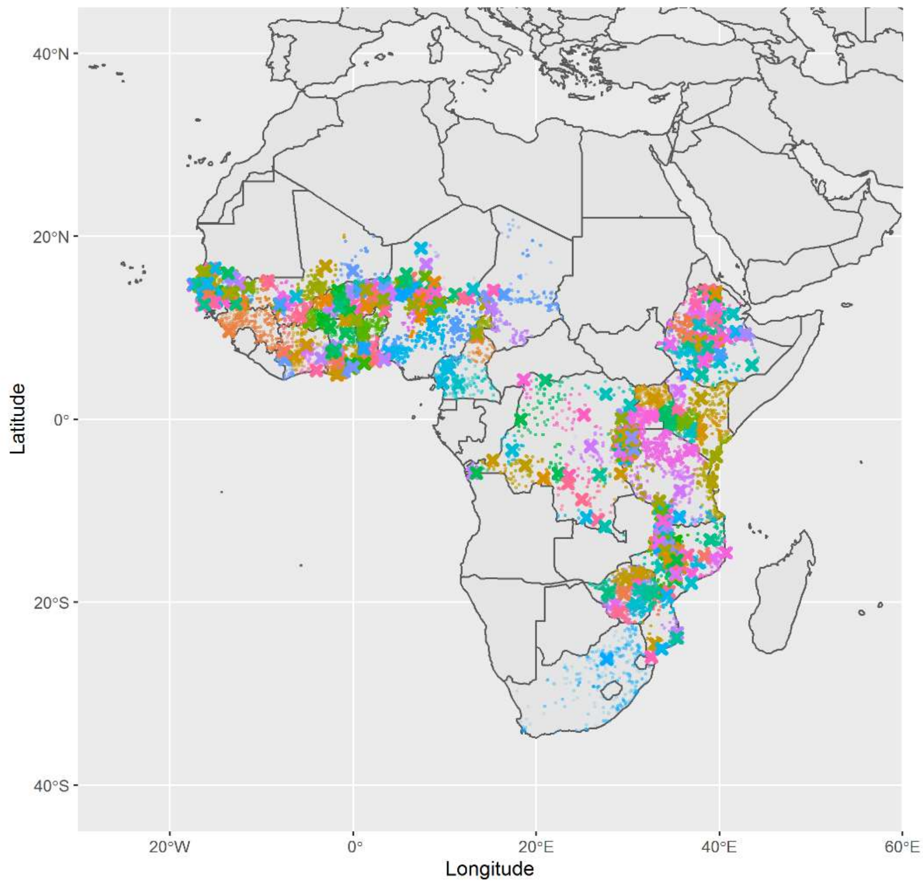

Figure 5.2 Household – market mapping shown for all survey years and markets with price data for the preceding 12 months.

access of the family members. Wealthier households score higher at the DHS wealth index[18], have a finished floor, or access to bought or piped water. Furthermore, maternal age and height may be related to a child's health and nutrition. Individual characteristics, such as sex, having siblings, or being a twin, channel how reduced food access eventually affects nutrition. We incorporate this individual-, parent-, and household-level information from the DHS dataset (Table 5.2). We include the aforementioned weather shock variables to control for the direct effects of weather on nutrition via health effects in some model specifications.

[18] https://dhsprogram.com/programming/wealth%20index/Steps_to_constructing_the_new_DHS_Wealth_Index.pdf

Table 5.1 Countries, markets, survey years, and households in the data

Country	**Number of markets**[1]	**Survey year**	**Number of households**[1]
Benin	21 (3.5%)	1998	1,667 (0.8%)
Burkina Faso	11 (1.8%)	2000	12,004 (5.4%)
Burundi	55 (9.1%)	2003	5,323 (2.4%)
Cameroon	15 (2.5%)	2004	4,653 (2.1%)
Chad	14 (2.3%)	2005	8,548 (3.9%)
Congo Democratic Republic	27 (4.5%)	2006	8,949 (4.0%)
Cote d'Ivoire	9 (1.5%)	2008	3,425 (1.5%)
Ethiopia	46 (7.6%)	2009	2,374 (1.1%)
Gambia	7 (1.2%)	2010	17,953 (8.1%)
Ghana	16 (2.7%)	2011	22,280 (10%)
Guinea	1 (0.2%)	2012	15,385 (6.9%)
Kenya	8 (1.3%)	2013	22,254 (10%)
Malawi	63 (10%)	2014	23,444 (11%)
Mali	53 (8.8%)	2015	19,826 (8.9%)
Mozambique	24 (4.0%)	2016	17,508 (7.9%)
Niger	57 (9.5%)	2017	10,071 (4.5%)
Nigeria	21 (3.5%)	2018	22,361 (10%)
Rwanda	75 (12%)	2019	2,887 (1.3%)
Senegal	55 (9.1%)	2020	1,109 (0.5%)
South Africa	1 (0.2%)		
Tanzania	5 (0.8%)		
Togo	5 (0.8%)		
Uganda	3 (0.5%)		
Zimbabwe	11 (1.8%)		
Total	603	Total	220,021

[1] n (%), Note: including incomplete cases with respect to other covariates

Table 5.2 Children-, parent-, and household-specific variables

Characteristic	**Rural, N = 288,455[1]**	**Urban, N = 100,806[1]**
Stunting	122,187 (42%)	27,416 (27%)
Haz	-169 (-270, -68)	-110 (-207, -15)
Underweight	67,334 (23%)	14,648 (15%)
Waz	-112 (-193, -34)	-75 (-152, 2)
Overweight	3,652 (1.3%)	1,939 (1.9%)
Diet diversity	1.00 (0.00, 3.00)	2.00 (0.00, 4.00)
Sex of child		
female	142,977 (50%)	49,779 (49%)
male	145,478 (50%)	51,027 (51%)
Age in months	30 (15, 44)	29 (15, 44)
Birth order number	3 (2, 5)	3 (1, 4)
Twin	8,113 (2.8%)	3,355 (3.3%)
Age mother	28 (24, 34)	28 (24, 34)
Height mother	1,580 (1,538, 1,623)	1,595 (1,553, 1,639)
Mother agri-occupation	121,729 (44%)	9,085 (9.6%)
Mother education		
higher	1,958 (0.7%)	6,480 (6.4%)
no education	155,764 (54%)	31,216 (31%)
primary	100,164 (35%)	30,861 (31%)
secondary	30,566 (11%)	32,240 (32%)
Father education		
higher	5,645 (2.1%)	11,285 (13%)
no education	127,557 (48%)	24,485 (28%)
primary	90,462 (34%)	21,258 (24%)
secondary	41,545 (16%)	30,519 (35%)
Wealth index		
middle	55,963 (22%)	11,822 (14%)
poor	144,392 (58%)	9,882 (11%)
rich	49,206 (20%)	65,594 (75%)
Floor material		
finished	97,122 (34%)	79,279 (79%)
unfinished	189,968 (66%)	21,030 (21%)
Water source		
bought	1,788 (0.7%)	4,692 (5.2%)
piped	47,888 (18%)	53,802 (59%)
surface	73,147 (28%)	5,466 (6.0%)
well	141,170 (53%)	26,823 (30%)
Has livestock	157,372 (77%)	29,539 (38%)
Has agricultural land	180,126 (84%)	27,592 (35%)

[1] n (%); Median (IQR)

We estimate separate linear models using different nutrition indicators as dependent variables. These include the diet diversity score alongside stunting, underweight, and overweight and their underlying z-scores. As the main explanatory variable of interest, the predicted mean unexpected price volatility is included using several time lags (preceding year, prebirth year, and postbirth year). Additional maize price indicators are tested as explanatory variables (i.e., general price volatility, positive and negative mean unexpected price volatility, non-averaged unexpected price volatility, and price level). We control for variables relevant to the child's nutrition (e.g., sex, birth order, siblings) and related to the household's characteristics (e.g., parents' education, mother's age and height, assets, wealth, ruralness). Some variables (wealth, ruralness) are interacted with the price variables to disentangle heterogeneity in price effects by household characteristics. As fixed effects we consider the survey year, the child's birth year, and the matched market to which the price data relates. The remaining variation explained by the coefficients should therefore be independent of time-invariant market characteristics and location-invariant annual specifics. For example, the fixed effects account for if children in the surrounding of a certain market are generally more food insecure or if a heat wave in one year affects nutrition across SSA.

Also, interrelations between the nutrition variables are possible. Changes in staple food prices may influence the anthropometric diet indicators through implications on diet diversity. Furthermore, interrelations between price levels and price volatility are also possible drivers affecting children's nutrition. For example, price spikes might have more severe implications for nutrition, if the price level is already at a high level.

Ordinary least squares specification:

$$D_c^i = \delta + \alpha V_{m,t}^j + \beta X_c + \gamma Z_h + \varepsilon_c \quad (1)$$

Fixed effects specification:

$$D_c^i = \alpha V_m^j + \beta X_c + \gamma Z_h + Y_c + B_c + M_m + \varepsilon_c \quad (2)$$

Additional time lags $z = \{t, b, b+1\}$:

$$D_c^i = \alpha V_{m,t}^j + \alpha' V_{m,b+1}^j + \alpha'' V_{m,b}^j + \beta X_c + \gamma Z_h + Y_c + B_c + M_m + \varepsilon_c \quad (3)$$

Weather shocks $R_{m,r}, T_{m,r}$:

$$D_c^i = \alpha V_{m,z}^j + \beta X_c + \gamma Z_h + Y_c + B_c + M_m + \omega R_{m,r} + \theta T_{m,r} + \varepsilon_c \quad (4)$$

Wealth and rural interactions with price indicators I_c^k:

$$D_c^i = \alpha V_{m,z}^j + \varphi V_{m,z}^j I_c^k + \beta X_c + \gamma Z_h + Y_c + B_c + M_m + \omega R_{m,r} + \theta T_{m,r} + \varepsilon_c \quad (5)$$

With $V_m^j = \left\{\overline{\widehat{V_{m,t,s}^{unexp}}}, \overline{V_{m,t,s}^{unexp}}, \overline{V_{m,t,s}^{+\,unexp}}, |\overline{V_{m,t,s}^{-\,unexp}}|, V_{m,t}^{gen}, \widehat{V_m^{unexp}}, V_{m,t,s}^{unexp}, \overline{P_{m,t,s}}\right\}$,

$D_c^i = \{stunting, haz, diet\ diversity\}$,

$X_c = \{age, sex, birth\ order, twin, birth\ interval\}$,

$Z_h = \{age\ mother, height\ mother, education\ parents, employment\ mother,$
$water\ source, floor\ material, livestock, agricultural\ land, ruralness, wealth\}$,

$z = \{t, b, b+1\}$, $I_c^k = \{ruralness, wealth\}$, $Y_c = survey\ year$, $B_c = birth\ year$,

$M_m = market$, $R_{m,r} = total\ rainfall\ in\ previous\ crop\ season$,

$T_{m,r} = mean\ temperature\ in\ previous\ crop\ season$

Diet diversity (6) and mean level prices (7) are added with no lag in two further specifications to Eq. (5). In the fixed effects regression we use clustered standard errors.

We focus on the fitted values for mean unexpected price volatility $\overline{\widehat{V_{m,t,s}^{unexp}}}$ from our price decomposition as main explanatory variable of interest. Here, we assume that the fitted values are entirely exogenous to the local market and capture the variation in price volatility that is driven by international futures prices and local weather shocks. Using these fitted values, we apply an instrumental variable approach in a two-stage procedure.

Second stage of the instrumental variable approach (exemplified for model specified in Eq. 5):

$$D_c^i = \alpha \overline{\widehat{V_{m,z}^{unexp}}} + \varphi \overline{\widehat{V_{m,z}^{unexp}}}\, I_c^k + \beta X_c + \gamma Z_h + Y_c + B_c + M_m + \omega R_{m,r} + \theta T_{m,r} + \varepsilon_c \quad \text{(II)}$$

For model specifications that explicitly include weather variables (Eq. 4–7), total rainfall and mean temperature cannot be regarded as instrumental variables. Unexpected futures volatility remains as sole instrument in these cases.

5.4 Results

5.4.1 *Price decomposition*

We aim to get a better understanding of the underlying drivers of unexpected local market price volatility. We use average monthly corn futures, local mean temperature, and total rainfall from the preceding crop-growing season. In Figure 5.3, the variables used for price decomposition are shown as averages across local markets between January 1994 and December 2017. For most of this period, corn futures and average local maize market prices converted to USD move in similar directions. Spikes and drops are more amplified in the futures market. Toward the end of the time interval, average local market prices diverge and increase, whereas futures follow a downward direction. For the local market prices in our dataset, the spread of market prices has increased since ~2008 and these divergences mostly continue until the end of 2017. Regarding weather variables, the average mean temperature remains comparably constant over this period. However, the average temperature across markets fluctuates within a smaller interval, between 20°C and 29°C, than the other variables do and already small differences in temperature might affect crop yields. Total rainfall reveals larger variability over time and strong differences across markets. To account for this variability in long-run local climate in our price decomposition, we control for market-, year-, and month-fixed effects in our econometric models.

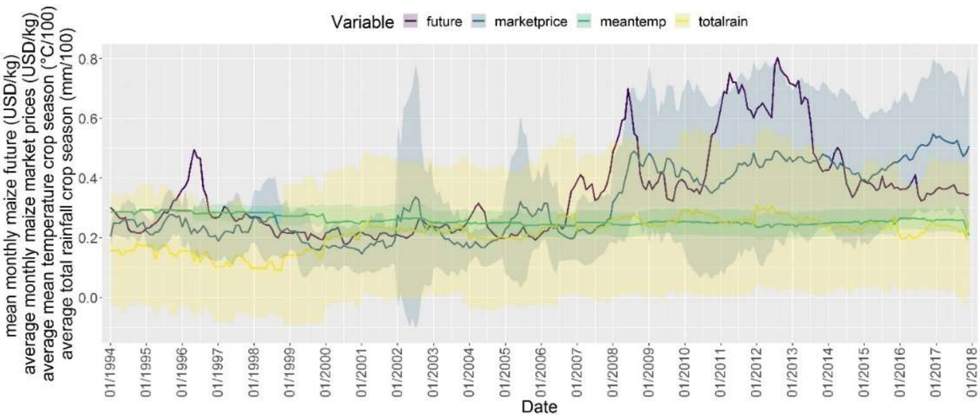

Figure 5.3 Market prices and potential drivers over time on average across markets

In Table 5.3 we compare how mean unexpected price volatility is affected by these drivers in six different model specifications. Increases in futures price volatility are correlated with local market price volatility. Effect sizes vary by model specification. Increasing mean temperature is also positively correlated with local prices, however, only if including year fixed effects. For total rainfall, we observe the opposite. It is associated with decreasing local price volatility if including year-fixed effects only. As shown by the coefficients of the interaction effects in the model specification including year-, month-, and market-fixed effects, the effects of futures volatility on local price volatility depend on mean temperature. That is to say, if the mean temperature is higher, the overall effect of futures is smaller. Therefore, the higher the temperature the less relevant futures volatility becomes for local price volatility. For example, drought has a critical effect on local production and prices. The effect of futures volatility on price volatility also depends on total rainfall. That is to say, the more it rains the larger the overall effect of futures. This implies that if local agriculture enjoys good conditions, futures volatility is more relevant to local prices.

Table 5.3 Mean unexpected price volatility decomposition results

	Mean unexpected price volatility					
	OLS	**OLS IE**	**2 FE**	**2 FE IE**	**3 FE**	**3 FE IE**
(Intercept)	**0.03*****	**0.04*****				
	(0.01)	(0.01)				
Mean unexpected futures volatility	**0.21*****	0.06	**0.14*****	0.04	**0.24*****	**0.56*****
	(0.01)	(0.04)	(0.01)	(0.04)	(0.02)	(0.03)
Mean temperature CS	**-0.00*****	**-0.00*****	**-0.12*****	**-0.12*****	**0.02*****	**0.02*****
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Total rainfall CS	**0.01**$^{\cdot}$	**0.01**$^{\cdot}$	**0.09*****	**0.08*****	-0.01	**-0.02***
	(0.00)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)
Mean unexpected futures volatility: mean temperature CS		**0.01*****		**0.00***		**-0.01*****
		(0.00)		(0.00)		(0.00)
Mean unexpected futures volatility: total rainfall CS		0.01		**0.06***		**0.13*****
		(0.03)		(0.03)		(0.02)
R^2	0.03	0.03				
Adj. R^2	0.03	0.03				
Num. obs.	42979	42979	42979	42979	42979	42979
R^2 (full model)			0.10	0.10	0.53	0.53
R^2 (proj model)			0.09	0.09	0.01	0.01
Adj. R^2 (full model)			0.09	0.09	0.52	0.52
Adj. R^2 (proj model)			0.08	0.08	-0.00	0.00
Num. groups: market			514	514	514	514
Num. groups: month			12	12	12	12
Num. groups: year					24	24

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$, Note: OLS =ordinary least squares, FE = fixed effects, IE = interaction effects

We find a considerable positive effect of mean unexpected futures volatility on mean unexpected price volatility. A linear model might, however, be limited in capturing the pathways of influence on local market price volatility. Therefore, we apply ML decomposition while controlling for nonseasonal futures volatility, local temperature, and rainfall.

CatBoostRegressor achieves scores in the train split of R^2_{train}=0.82 and R^2_{test}=0.80 in the test data split. We assess the sensitivity of results with respect to the chosen technique by comparing the scores of different ML models (Appendix). CatBoostRegressor has the advantage that it can include markets as categorical variable. The score levels are convincing and their difference between training and test set are within reasonable limits. We use

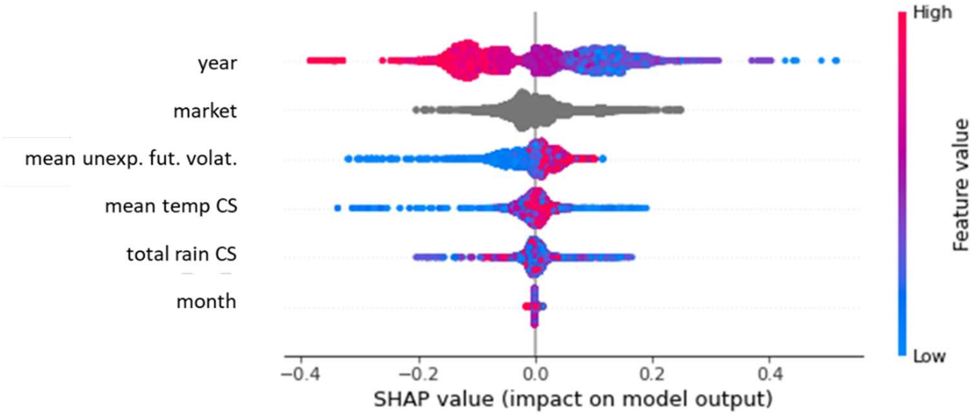

Figure 5.4 Shapley value decomposition from CatboostRegressor

random splits for all models. We do not include interaction effects between futures volatility, temperature, and rainfall in the ML models, as ML models automatically captures variable interactions.

Figure 5.4 presents the results of the Shapley value decomposition, wherein features are ordered by their mean Shapley values. The order aligns with the effect size provided from the fixed-effects regression previously shown in Table 5.3. More recent years appear to relate to lower or more negative mean unexpected volatility. Apart from year and market effects, mean unexpected futures volatility shows the largest impact, and low (and negative) futures volatility values have a decreasing effect on market price volatility. The opposite holds for positive futures volatility values, although the impact size on price volatility tends to be smaller. Low temperatures and rainfall affect price volatility in a less clear direction. Overall, this implies context-specificity of local effects related to weather shocks on unexpected price volatility.

We address endogeneity in the subsequent nutrition-price analysis by using the market, month, and year fixed effects model including interaction effects as first stage of our two-stages instrumental variable approach. The fitted values of this specification are used as the main variable of interest in explaining nutrition outcomes in the following.

5.4.2 *Nutrition–price analysis*

To disentangle how price volatility affects children's nutrition, we compare a multitude of model specifications. For six nutrition indicators (i.e., stunting, haz, underweight, overweight, waz, diet diversity), we show the coefficients for five[19] price volatility measures in up to seven model specifications related to the year prior to the household survey in Figure 5.5. Interaction effects for model specifications 5-7 are not accounted for in this visualization. Since we use linear specifications in all cases for better comparability between the models, the predicted values for the binary z-score indicators might fall outside the boundaries of the actual indicator.

Most model specifications support the conclusion that higher price volatility increases the occurrence of stunting in children, especially when controlling for time- or location-invariant factors as fixed effects (2), additional time lags (3), weather shocks (4), and interaction effects (5). While mean unexpected price volatility has a relatively small effect on stunting on its own, when we separate it into its average positive and negative components, we find that price spikes and drops have a strong effect on stunting. The effect is however not statistically significant for price drops. Thus, strongly positive and strongly negative unexpected price volatility both relate to stunting. In comparison, general volatility, that captures expected and unexpected price changes, shows an increasing effect on stunting in almost all specifications, however, the effect sizes are small and rarely statistically significant. The estimates of the directly calculated price indicators might be subject to endogeneity issues. In contrast, the predicted mean unexpected volatility values are unlikely to be affected by changes in local food markets. For the predicted mean unexpected volatility we find large and significant increasing impacts on stunting across fixed effects model specifications.

The direction of the effects of price volatility on the stunting indicator are widely supported by their effects on the haz score. The DHS haz score is the basis for the stunting indicator, but it captures more diversity in nutrition

[19] The underlying non-averaged unexpected price volatility and its prediction is furthermore compared to the other price indicators in the Appendix. We left these variables out here to present more comparable indicators related to the preceding 12 months to the survey. The comparison to price levels is also shown only in the Appendix.

outcomes [−600,600]. The predicted mean unexpected volatility suggests a clear negative effect on haz, which implies a worsening of the nutrition outcome. Interestingly, this effect is significantly stronger for households that are classified rich on the wealth index as revealed by the interaction effects. The nutrition of children in richer households might have more 'room' to worsen as they have higher haz scores on average to begin with. Also, they are less likely subsistence farmers and might suffer from a negative correlation between price volatility and their potential agricultural assets. The latter is supported by the fact that being urban reduces the negative implications of price volatility on the haz score, even though the coefficients for this interaction effect are not statistically significant (see full regression table in Appendix).

Overall, the waz indicator that underlies both binary indicators, underweight and overweight, switches signs across model specifications. However, for most fixed effects specifications testing the effect of unexpected volatility on the waz score, we find a negative effect that is especially strong for the predicted mean unexpected volatility. For price spikes, the effect direction turns once controlling for diet diversity and price levels in the regression. Complementarily, for price drops a strong and significant negative effect becomes apparent once controlling for price levels. The complementary effect is also revealed in our underweight analysis. This suggests that implications of price levels are subsumed in in the effects of price drops if not controlled for explicitly. Besides this, price volatility in the year prior to the survey tends to increase underweight. However, effect sizes are smaller compared to the stunting results and rarely significant. For overweight, we find a reducing effect of price volatility over the previous year. Effect sizes are however close to zero. The largest reductions are found for price drops.

Diet diversity tends to be reduced under mean unexpected price volatility, price drops, and predicted mean unexpected price volatility using the instrumental variable approach. Any significant effects in the fixed effects models however vanish once further control variables are added. Positive price volatility affects diet diversity insignificantly, nevertheless, effect directions are unexpectedly mostly positive. However, the interaction effect of preceding year positive mean unexpected volatility with being an urban

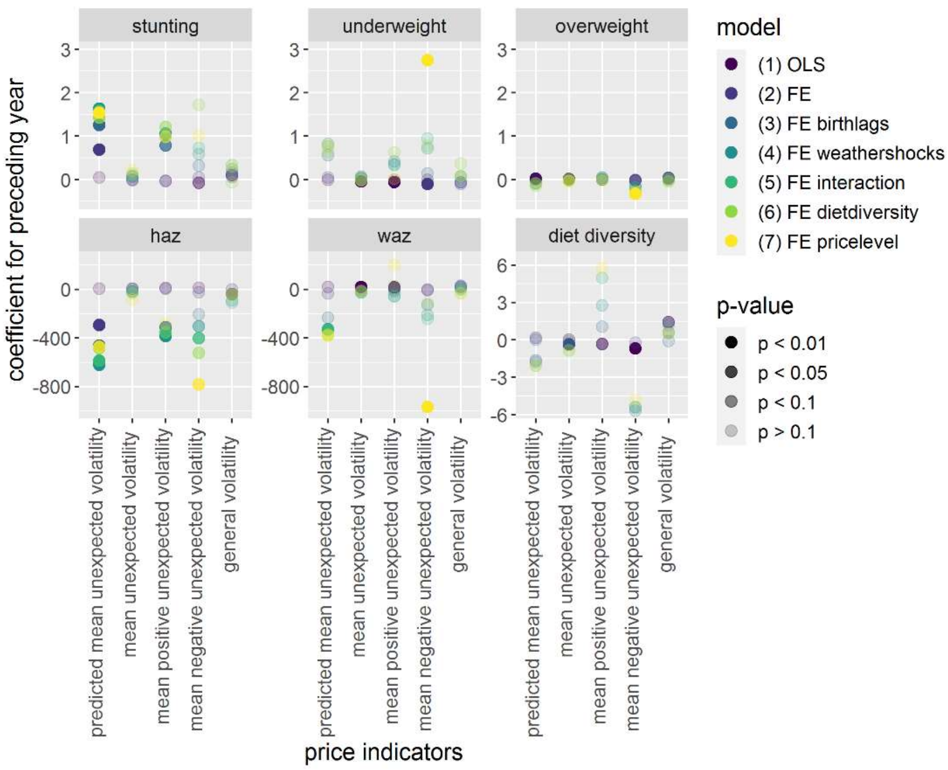

Figure 5.5 Multi-regression results of nutrition-price analysis

household is significantly negative and the effect size exceeds the size of the non-interacted coefficient for poor urban households. This indicates that for children in poor, urban households indeed diet diversity is reduced as a consequence of positive price volatility in the previous year since they might be especially reliant on food purchases on the market.

Although our instrumental variable approach reveals large and significant effects for stunting and haz, it does not identify similar effects for other nutrition indicators. The differentiation by level of wealth, and based on the rural–urban household, and agricultural producer–food consumer divides discloses a heterogeneity hidden in the previously discussed results. Furthermore, disentangling price spikes from price drops appears relevant to how price volatility affects nutrition. Next, we take a closer look at the impact of price volatility on children’s nutrition by comparing subsets of data.

As discussed in the conceptual framework, rural and urban households are probably affected differently by price shocks. Table 5.4 presents the regression results for the model specification in Eq. (4) for stunting and predicted mean unexpected volatility while controlling for price volatility values in the 12 months before and after birth, and local weather shocks. Furthermore, we compare different wealth groups and constructed groups of likely agricultural producers (agriprod) and food consumers in urban areas (foodcon). Agricultural producers are defined as being rural, as having livestock or agricultural land, and as households with the mother being occupied in agriculture. Urban food consumers on the other hand are classified as urban, having neither livestock nor agricultural land, and being not employed in agriculture.

A higher predicted mean unexpected volatility during the preceding year is related to a higher occurrence of stunting across household groups. The effects are particularly large and significant for rural, agricultural, and poor households. Boys are significantly more exposed to stunting than girls, however, the effect is rather small. Being a twin is also related to stunting, especially in rural, less wealthy, or farming households. Furthermore, limited parental education increases the occurrence of stunting across various subgroups. Interestingly, for agricultural producers stunting increases if water is not bought. This effect could be the result of an underlying split of producers into those with market access and those that are truly remote. Also, a higher predicted mean unexpected volatility around the 12 months before and after birth is related to reduced stunting, especially among children in rural households. Potentially, higher volatility around the time of birth might cause adjustments in storage and selling behavior preventing stunting later on. It could alternatively cause a higher rate of miscarriage or a lower rate of pregnancies to begin with (Grace et al., 2014).

Higher temperature during the previous crop season appears to reduce stunting, especially for poor and rural households. Higher rainfall has an increasing effect on stunting for agricultural producers. Since the effects of weather on yields is captured in the predicted price volatility, these effects show the effect of weather on stunting through other channels. Effect directions are counter-intuitive on the first sight. The interpretation of these effect requires more in-depth analyses.

For diet diversity, the aggregated analysis summarized in Figure 5.5 has suggested that effects related to price volatility indicators of the preceding year are rather insignificant and increased positive mean unexpected volatility is diet diversity enhancing, even if insignificantly. In the following, we want to disentangle these effects by having a closer look at different age groups, because the child's age significantly increases diet diversity in our multi-model comparison (see Appendix and Table 5.5). This is naturally inherent to the indicator, since younger children are often largely breast-fed. On the other hand, for children older than 2, the DHS variables underlying the diet diversity index are less consistently collected than for the anthropometric indicators (Figure 5.9 in the Appendix). We therefore compare fixed effects regressions using predicted, positive and negative mean unexpected price volatility and their effects on diet diversity for all, young (younger than 2 years of age) and old (older than 2 years of age) children. Results for price volatility impacts on diet diversity are summarized in Table 5.5. Here, an adjusted specification of Model 4 is used without time lags as complete observations for diet diversity are limited and too few if also price data around birth must be available (see the full Model 4 specification in the Appendix).

Table 5.4 Regression results stunting – Predicted mean unexpected volatility

Stunting	**Predicted mean unexpected volatility**							
	full	**rural**	**urban**	**poor**	**middle**	**rich**	**agriprod**	**foodcons**
Preceding year	**1.63*****	**2.05****	0.96	**2.92****	1.99	**1.12**$^{\cdot}$	**2.04***	1.00
	(0.47)	(0.77)	(0.60)	(0.95)	(1.38)	(0.60)	(0.96)	(0.67)
Postbirth	**-0.22***	**-0.29***	-0.11	-0.20	-0.25	-0.21	-0.07	-0.22
	(0.11)	(0.12)	(0.21)	(0.17)	(0.23)	(0.16)	(0.17)	(0.28)
Pre_birth	**-0.29***	**-0.28***	-0.32	**-0.28**$^{\cdot}$	-0.05	**-0.39***	0.14	-0.27
	(0.12)	(0.12)	(0.27)	(0.16)	(0.27)	(0.18)	(0.18)	(0.35)
Urban	**-0.05*****			-0.01	0.02	**-0.07*****		
	(0.01)			(0.02)	(0.02)	(0.01)		
Poor	**0.03*****	**0.04*****	0.02				**0.03****	0.05
	(0.01)	(0.01)	(0.02)				(0.01)	(0.05)
Rich	**-0.04*****	**-0.03***	**-0.07*****				-0.03	**-0.07***
	(0.01)	(0.01)	(0.02)				(0.02)	(0.03)
Male	**0.03*****	**0.03*****	**0.02**$^{\cdot}$	**0.03*****	**0.04****	**0.02**$^{\cdot}$	**0.04*****	**0.02**$^{\cdot}$
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Birth order	**0.01*****	**0.01*****	**0.01****	**0.01****	**0.01***	**0.01*****	0.01	**0.01***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.01)
Age mother	**-0.01*****	**-0.01*****	**-0.01*****	**-0.00*****	**-0.01***	**-0.01*****	**-0.00**$^{\cdot}$	**-0.01*****
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Mother no education	**0.13*****	**0.12****	**0.13*****	**0.33****	0.02	**0.12*****	-0.10	**0.11****
	(0.02)	(0.04)	(0.02)	(0.12)	(0.09)	(0.02)	(0.22)	(0.04)
Mother primary educ.	**0.12*****	**0.11****	**0.12*****	**0.32****	0.02	**0.11*****	-0.09	**0.10****
	(0.02)	(0.04)	(0.02)	(0.12)	(0.09)	(0.02)	(0.21)	(0.03)
Mother secondary educ.	**0.07*****	0.06	**0.06****	**0.27***	-0.02	**0.05****	-0.13	0.03
	(0.02)	(0.04)	(0.02)	(0.12)	(0.09)	(0.02)	(0.22)	(0.03)
Mother agri-occup.	0.00	-0.00	0.03	0.00	0.00	0.01		
	(0.01)	(0.01)	(0.02)	(0.01)	(0.02)	(0.01)		
Father no education	**0.08*****	**0.10*****	**0.06*****	0.05	0.07	**0.09*****	**0.14*****	**0.06****
	(0.02)	(0.02)	(0.02)	(0.04)	(0.05)	(0.02)	(0.04)	(0.02)
Father primary educ.	**0.06*****	**0.09*****	**0.05****	0.04	0.05	**0.05****	**0.13*****	**0.03**$^{\cdot}$
	(0.01)	(0.02)	(0.02)	(0.04)	(0.04)	(0.02)	(0.04)	(0.02)
Father secondary educ.	**0.04****	**0.07****	**0.02**$^{\cdot}$	0.00	0.05	**0.04****	**0.10***	0.02

Stunting	Predicted mean unexpected volatility							
	full	**rural**	**urban**	**poor**	**middle**	**rich**	**agriprod**	**foodcons**
	(0.01)	(0.02)	(0.01)	(0.04)	(0.04)	(0.01)	(0.04)	(0.01)
Unfinished floor	**0.03*****	**0.02***	**0.04****	0.01	0.02	**0.04****	0.00	0.04
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.03)
Piped water	**0.04**$^{\cdot}$	**0.10**$^{\cdot}$	**0.04**$^{\cdot}$	0.07	**0.22****	0.03	**0.28**$^{\cdot}$	0.03
	(0.03)	(0.05)	(0.02)	(0.07)	(0.07)	(0.02)	(0.15)	(0.02)
Surface water	**0.06***	**0.09**$^{\cdot}$	**0.09****	0.06	**0.22****	0.04	**0.29***	0.07
	(0.03)	(0.05)	(0.03)	(0.07)	(0.07)	(0.03)	(0.14)	(0.05)
Well water	0.04	0.09	0.03	0.06	**0.20****	0.03	**0.29***	0.03
	(0.03)	(0.06)	(0.02)	(0.07)	(0.06)	(0.02)	(0.14)	(0.02)
Height mother	**-0.00****	**-0.00***	**-0.00**$^{\cdot}$	-0.00	**-0.00*****	**-0.00***	**-0.00*****	**-0.00*****
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Has livestock	**-0.02**$^{\cdot}$	**-0.02***	**-0.02**$^{\cdot}$	**-0.02**$^{\cdot}$	**-0.06****	0.00		
	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.01)		
Has agri-land	**0.02****	**0.02**$^{\cdot}$	0.01	-0.01	**0.07****	0.01		
	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.01)		
Twin	**0.09*****	**0.11*****	**0.04**$^{\cdot}$	**0.10*****	**0.12***	**0.06***	**0.13*****	0.01
	(0.02)	(0.03)	(0.02)	(0.03)	(0.05)	(0.03)	(0.03)	(0.03)
Age in months	**0.01*****	**0.01*****	**0.00***	**0.01*****	**0.01****	**0.00***	**0.01****	**0.00**$^{\cdot}$
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Distance househ.-market	0.00	0.00	-0.00	0.00	-0.00	-0.00	**0.00***	-0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Total rainfall CS	-0.00	0.06	-0.16	-0.06	-0.08	0.06	**0.37**$^{\cdot}$	-0.06
	(0.13)	(0.14)	(0.14)	(0.19)	(0.19)	(0.15)	(0.20)	(0.17)
Mean temperature CS	**-0.06****	**-0.08***	-0.03	**-0.13****	-0.09	-0.03	-0.04	-0.07
	(0.02)	(0.03)	(0.03)	(0.04)	(0.06)	(0.03)	(0.05)	(0.06)
Num. obs.	35127	24865	10262	15085	6930	13112	9835	5344
R^2 (full model)	0.12	0.09	0.15	0.08	0.11	0.14	0.10	0.16
R^2 (proj model)	0.05	0.03	0.04	0.02	0.03	0.04	0.04	0.04
Adj. R^2 (full model)	0.11	0.07	0.13	0.06	0.07	0.12	0.08	0.12
Adj. R^2 (proj model)	0.04	0.02	0.02	-0.00	-0.01	0.02	0.02	-0.00
Num.	293	279	209	264	251	258	235	173

Stunting	Predicted mean unexpected volatility							
	full	**rural**	**urban**	**poor**	**middle**	**rich**	**agriprod**	**foodcons**
groups: market								
Num. groups: year	9	9	9	9	9	9	9	9
Num. groups: birth_year	16	16	16	16	16	16	16	16

***$p < 0.001$; **$p < 0.01$; *$p < 0.05$; ·$p < 0.1$

Predicted mean unexpected volatility prior to the survey reduces diet diversity, most significantly and strongly for younger children. Being urban and rich and having better educated parents in general increases diet diversity across models. A higher level of rainfall in the preceding crop season reduces diet diversity. A higher temperature tends to increase diet diversity, especially among young children. Weather effects should represent direct implications on diet diversity not conveyed through the market price since weather is controlled for in the predicted volatility. Nevertheless, the effect is not intuitive. A high level of positive MUV reduces diet diversity insignificantly. If negative MUV becomes less strong, diet diversity among young and urban children increases and also among older, rich children as shown with the interaction effects. The effect of children in richer households might be larger here since their diet diversity is overall higher and contains more potential for deterioration than in poorer households.

Table 5.5 Regression results diet diversity – PMUV, positive and negative MUV

Diet diversity	PMUV			Positive MUV			Negative MUV		
	full	**young**	**old**	**full**	**young**	**old**	**full**	**young**	**old**
Preceding year	-1.48	**-19.00*****	**-4.07**$^{\cdot}$	-0.50	-0.39	-0.78	-0.27	-0.73	-0.33
	(1.63)	(2.54)	(2.43)	(0.56)	(0.26)	(1.09)	(0.38)	(0.74)	(0.38)
Urban	**0.11****	0.06	**0.16*****	**0.08**$^{\cdot}$	0.07	0.10	**0.12****	0.07	**0.17****
	(0.04)	(0.04)	(0.05)	(0.05)	(0.05)	(0.06)	(0.04)	(0.05)	(0.05)
Poor	**-0.12*****	**-0.07***	**-0.17*****	**-0.09**$^{\cdot}$	**-0.07**$^{\cdot}$	**-0.11***	**-0.13****	**-0.07***	**-0.18*****
	(0.03)	(0.03)	(0.04)	(0.05)	(0.04)	(0.05)	(0.04)	(0.03)	(0.05)
Rich	**0.12*****	**0.08***	**0.14****	**0.15****	**0.09***	**0.18****	**0.10***	0.04	**0.13****
	(0.04)	(0.03)	(0.04)	(0.05)	(0.05)	(0.06)	(0.04)	(0.04)	(0.05)
Male	0.01	0.01	0.01	0.01	0.02	0.00	0.00	0.01	-0.00
	(0.02)	(0.02)	(0.02)	(0.02)	(0.03)	(0.03)	(0.02)	(0.02)	(0.03)
Birth order	0.00	**-0.01**$^{\cdot}$	-0.00	0.01	**-0.02***	0.01	-0.00	-0.01	-0.01
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Age mother	**0.01***	**0.01****	**0.01***	0.00	**0.01****	0.01	**0.01***	**0.01***	**0.01***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Mother no education	**-0.23***	-0.04	**-0.43****	**-0.21**$^{\cdot}$	-0.09	**-0.34**$^{\cdot}$	**-0.22***	-0.05	**-0.44***
	(0.09)	(0.08)	(0.16)	(0.12)	(0.12)	(0.20)	(0.10)	(0.08)	(0.18)
Mother primary educ.	**-0.18**$^{\cdot}$	-0.02	**-0.37***	-0.17	-0.10	-0.25	-0.17	-0.02	**-0.38***
	(0.10)	(0.07)	(0.16)	(0.12)	(0.11)	(0.21)	(0.11)	(0.08)	(0.18)
Mother secondary educ.	-0.08	0.03	-0.22	-0.08	-0.09	-0.08	-0.05	0.05	-0.22
	(0.09)	(0.07)	(0.16)	(0.12)	(0.11)	(0.21)	(0.11)	(0.08)	(0.18)
Mother agri-occup.	**0.08**$^{\cdot}$	**0.12*****	0.07	0.02	**0.09***	0.00	0.05	**0.11****	0.04
	(0.04)	(0.03)	(0.05)	(0.05)	(0.04)	(0.06)	(0.05)	(0.04)	(0.06)
Father no education	**-0.10**$^{\cdot}$	-0.04	-0.12	-0.09	-0.04	-0.10	-0.08	-0.02	-0.10
	(0.06)	(0.06)	(0.08)	(0.09)	(0.09)	(0.12)	(0.07)	(0.08)	(0.09)
Father primary educ.	**-0.10**$^{\cdot}$	-0.05	-0.11	**-0.15***	-0.10	-0.17	-0.08	-0.05	-0.10
	(0.05)	(0.06)	(0.07)	(0.07)	(0.08)	(0.11)	(0.06)	(0.07)	(0.08)
Father secondary educ.	**-0.11***	**-0.09**$^{\cdot}$	**-0.12**$^{\cdot}$	**-0.13**$^{\cdot}$	-0.11	-0.14	**-0.11***	-0.10	-0.13
	(0.05)	(0.05)	(0.07)	(0.07)	(0.07)	(0.11)	(0.05)	(0.06)	(0.08)
Unfinished floor	-0.01	-0.02	0.01	0.03	0.04	0.02	-0.03	-0.05	-0.00

Diet diversity	PMUV			Positive MUV			Negative MUV		
	full	**young**	**old**	**full**	**young**	**old**	**full**	**young**	**old**
	(0.04)	(0.04)	(0.05)	(0.05)	(0.05)	(0.06)	(0.04)	(0.04)	(0.05)
Piped water	-0.04	-0.05	-0.06	0.07	0.07	0.08	-0.04	-0.04	-0.06
	(0.11)	(0.10)	(0.16)	(0.12)	(0.12)	(0.17)	(0.12)	(0.10)	(0.16)
Surface water	-0.09	-0.10	-0.09	-0.03	-0.05	0.00	-0.10	-0.11	-0.08
	(0.11)	(0.10)	(0.15)	(0.11)	(0.12)	(0.16)	(0.11)	(0.11)	(0.15)
Well water	-0.07	-0.10	-0.08	0.05	0.03	0.07	-0.09	-0.10	-0.07
	(0.10)	(0.09)	(0.15)	(0.10)	(0.11)	(0.16)	(0.11)	(0.09)	(0.15)
Height mother	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00	0.00	-0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Has livestock	0.05	0.00	**0.07**$^{\cdot}$	0.05	-0.01	0.08	0.03	-0.01	0.05
	(0.03)	(0.03)	(0.04)	(0.05)	(0.04)	(0.06)	(0.04)	(0.04)	(0.04)
Has agri-land	0.00	0.03	-0.01	0.05	**0.10**$^{\cdot}$	0.03	-0.03	-0.01	-0.04
	(0.03)	(0.04)	(0.03)	(0.04)	(0.05)	(0.05)	(0.03)	(0.03)	(0.04)
Twin	-0.01	0.04	-0.06	-0.09	-0.04	-0.13	0.02	0.08	-0.04
	(0.06)	(0.06)	(0.10)	(0.08)	(0.07)	(0.12)	(0.07)	(0.08)	(0.11)
Age in months	**0.04*****			**0.03*****			**0.03*****		
	(0.00)			(0.01)			(0.00)		
Distance househ.-market	-0.00	0.00	-0.00	-0.00	-0.00	-0.00	-0.00	0.00	-0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Total rainfall CS	**-0.94****	**-1.47*****	**-0.78**$^{\cdot}$	-0.18	**-1.76***	-0.20	**-0.77***	-0.61	-0.45
	(0.33)	(0.43)	(0.45)	(0.62)	(0.80)	(0.87)	(0.37)	(0.57)	(0.44)
Preceding year:Urban	-0.04	**0.58*****	0.19	0.08	**0.50****	0.25	-0.13	-0.02	-0.01
	(0.14)	(0.15)	(0.19)	(0.14)	(0.18)	(0.21)	(0.14)	(0.16)	(0.19)
Num. obs.	49740	23274	26466	30937	14314	16623	38654	18019	20635
R^2 (full model)	0.20	0.19	0.19	0.22	0.20	0.22	0.20	0.20	0.20
R^2 (proj model)	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02
Adj. R^2 (full model)	0.19	0.17	0.18	0.21	0.18	0.20	0.19	0.18	0.18
Adj. R^2 (proj model)	0.01	-0.00	-0.00	0.00	-0.02	-0.01	0.01	-0.01	-0.00
Num. groups: market	361	355	357	319	314	313	297	292	292
Num. groups: year	11	11	11	11	11	11	10	10	10

Diet diversity	PMUV			Positive MUV			Negative MUV		
	full	young	old	full	young	old	full	young	old
Num. groups: birth_year	20	17	17	20	17	17	20	17	17

Note: PMUV = predicted mean unexpected price volatility, MUV = mean unexpected price volatility

5.5 Discussion

Our price decomposition reveals that local market price volatility is significantly driven by futures volatility and local weather shocks. Our econometric and ML results suggest that futures volatility is a considerably strong driver. Our findings are in line with Brown and Kshirsagar (2015) who show that international prices and domestic weather disturbances affect local market prices. Thus, our analysis confirms these assumed links depicted in our conceptual framework and supports the use of futures volatility and, for some model specifications, weather variables as instruments in the nutrition-price analysis.

We base our definition of unexpected nonseasonal food price volatility on Amolegbe et al. (2021), who investigate the effect of domestic and imported rice price volatility on household diet diversity for different wealth groups in Nigeria. In the study at hand, we find that predicted mean unexpected maize price volatility in the preceding year reduces diet diversity. Amolegbe et al. (2021) also find that dietary diversity decreases with imported rice price volatility. Our predicted price volatility is strongly driven by unexpected corn futures volatility and might therefore be considerably related to import prices. The interaction effects with wealth however do not suggest comparably strong differences between poor and rich households as found for imported rice volatility (Amolegbe et al., 2021).

The domestic rice price volatility effects found by Amolegbe et al. (2021) tend to be diet diversity-increasing, apart from agriculturally producing households and those with very diversified diets. This is not clearly supported by our main results (compare Figure 5.5, Table 5.5). Thus far, we have compared the results of Amolegbe et al. (2021) with our results based on 12-months-average price indicators. The non-predicted and non-averaged unexpected nonseasonal volatility should, however, be closest to their specification. If we consider these results, we find significantly positive effects on diet diversity for poor households (see Appendix). For urban households, unexpected volatility reduces diet diversity although the effect is not statistically significant. Thus, the positive effect of very short-term unexpected price volatility on diet diversity might be driven by additional income received by agricultural households. However, this interpretation is not supported by the findings of Amolegbe et al. (2021). Furthermore, if only staple food prices increase, a short-term strategy for households might include increasing consumption of other foods to diversify their diets. However, this effect does not seem to prevail for the 12-months-average indicators. This might imply subsequent price increases for substituting foods and a focus on staples in the medium term.

In our study, we focus on local market maize prices to investigate their influence on children's nutrition. Although maize is an important staple food in the region being studied, nutrition is influenced by the overall dietary composition and the prices of other foods (Headey et al., 2018). Nonetheless, maize is a key component of diets in SSA; hence, the implications of changes in maize access must be well understood. The nutritional implications of price volatility of other food products will complement our findings in future research.

For assessing diet diversity, our results stress the importance of distinguishing children by age as the underlying food group consumption data were collected more consistently for younger children. Further analyses should focus on the age comparison in more depth, potentially for a subset of most complete data.

Diet diversity and nutritional stability are linked to crop diversity (Nicholson et al., 2021). However, farm-level production diversity is not found to improve child nutrition generally (Khonje et al., 2022). Nevertheless, to account for the link between diet diversity and anthropometric nutrition indicators, we include diet diversity from the preceding year in our Model 6 for multi-regression analysis. For example, the impact of predicted mean unexpected price volatility on stunting is reduced when diet diversity is controlled in comparison to Model 5. However, it remains significantly positive. Further investigations of our data should differentiate price volatility impacts on changes in nutrition and be conducted by explicitly controlling for the actual level of (mal-) nutrition.

Apart from the child's age, we find that the heterogeneity of household location and wealth matters in terms of how children's nutrition is affected by price volatility. We find that children are significantly more affected by stunting if they live in rural, poor, or agriculturally producing households (Table 5.4). For anthropometric nutrition indicators (all apart from diet diversity), we are confident that rolling 12-month average volatility indicators are more relevant than a very short-term volatility measure that might be more meaningful for assessing the impacts on diet diversity.

In some models, we find that higher volatility occurring around the time of a child's birth counteracts the effects of volatility in the preceding year. For example, higher predicted unexpected volatility in the year before birth significantly reduces stunting (Appendix). This finding contrasts with that of previous research, which shows that food price inflation during pregnancy and infancy increases the risk of stunting significantly (Woldemichael et al., 2022). However, high volatility around birth might cause behavioral changes in storage and selling behavior, which might reduce malnutrition later on. Alternatively, price volatility could also cause families to delay pregnancies or miscarriage (Grace et al., 2014). In this case, our results for the price effects around birth could be driven by households with generally lower risk of food insecurity. Nonetheless, price volatility around birth and in the preceding year could also be correlated. Including market-fixed effects should partially account for market-specific trend correlation. Interestingly, Grace et al. (2014) find a positive correlation between pre-pregnancy maize prices and birthweight. However, for price levels before birth, our models suggest neither a clear nor significant improvement of child nutrition (see Appendix). Overall, although effect directions for price indicators around the time of birth are not necessarily intuitive, their consideration is relevant. They show considerable effect sizes and increase effect size of the price indicator for the year before the survey if controlled for in the regression. Therefore, the implications of price volatility around the time of birth demands further investigation.

Weather shocks during the maize growing season can affect child nutrition indirectly through the impact of weather on yields and thus food production, availability, and access. Additionally, weather extremes can affect nutrition through health effects caused by heat stress, disease, or clean water scarcity (Brown et al., 2014; Cooper et al., 2019; Gebre and Rahut, 2021; Grace et al., 2021; McMahon and Gray, 2021; Nawrotzki et al., 2016). High temperatures during the maize growing season are found to significantly reduce the weight-for-height z-score among rural children in SSA (Baker and Anttila-Hughes, 2020). In our anthropometric haz- and waz-score models, that are likely picking up rather chronic malnutrition in contrast to the whz-score, effect direction of mean temperature in the previous crop season is positive, indicating a nutrition improvement. The effect of weather through yields on prices is however already captured in our predicted price volatility indicators that have a reducing effect on those scores. Here, the positive relation between temperature and z-scores should be driven by another channel than prices. If we do not use the predicted volatility measures but the directly calculated ones, temperature effects on both z-scores vary regarding their directions and are not statistically significant. Still, the positive effect sign for temperature in the predicted volatility model violates the assumptions that higher temperatures negatively affect children's nutrition through health. Our linear model specification might be limited in its ability to disentangle the relationship between weather shocks and nutritional outcomes that is, for example, fitted to a fourth order polynomial model in Baker and Anttila-Hughes (2020). In general, we use linear specifications in all models to facilitate comparability und interpretability of effects. However, the extant literature discusses whether other model types are more useful in providing a complete representation of nutrition patterns (Sweeney et al., 2013). Other than that, our weather variables indicate mean temperature and total rainfall in a crop season, which are not necessarily extreme events. Moreover, weather events in another time period could be more relevant for assessing the direct effect of weather on nutrition that does not channel through food prices. A more in-depth exploration of weather variables could help disentangling these counterintuitive effect signs. Nonetheless, effect sizes for weather and rainfall are considerable. The inclusion of these variables in the model specification reveals a strong influence on the effect of predicted mean unexpected volatility on the haz score, which is relevant to consider and explore in more depth.

By using predicted mean unexpected volatility, we employ weather variables and futures volatility as instruments to avoid endogeneity problems caused by simultaneity in nutrition outcomes and market prices which might influence each other through market supply and demand. Therefore, the resulting estimates might be interpreted as causal effects of unexpected nonseasonal maize price volatility on nutrition.

Following Amolegbe et al. (2021), we focus our analysis on nonseasonal, detrended price movements, which we refer to as "unexpected volatility". However, this interpretation deviates from price volatility measures based on standard deviations that are often used (Brümmer et al., 2016; Kornher and Kalkuhl, 2013). For comparison, we compute a standard-deviation based "general volatility" measure as price indicator and include it in our multi-regression attempt. We find that an increase in general volatility also increases stunting in almost all specifications although mostly insignificantly (Figure 5.5, Appendix). Analyses based on longer, continuous price time-series data alternatively use (generalized) autoregressive conditional heteroskedastic models to measure unpredictable price volatility (e.g., Maître d'Hôtel and Le Cotty, 2018; Minot, 2014). We find that this approach is not well applicable to our highly unbalanced price dataset. Nevertheless, further analysis of our data might include other specifications of price volatility, such as the standard deviation of the unexpected volatility measure.

Our data only allows us to differentiate between net food producing households, including sellers and subsistence farmers, and food purchasing households, to a limited extent. We distinguish between rural and urban households and include information about the possession of agricultural land and livestock and about the mother's employment in agriculture. However, a clear distinction between net producers and buyers is impossible, wherein the resulting effects could still be the outcome of opposing mechanisms of both household types. Nonetheless, livestock ownership is nutrition improving across models, which agrees with previous research (Khonje et al., 2022).

In our instrumental variable approach, we account for price transmissions from international markets by including corn futures volatility as instrument. We do not capture other trade effects such as imported food prices (Amolegbe et al., 2021), trade policies (Bekkers et al., 2017; Smith and Glauber, 2020) or trade openness (Mary, 2019). A possible extension of our analysis should explicitly account for global market integration at the country level, which has the potential to stabilize nutrition (Nicholson et al., 2021). Additionally, the accessibility of and trade at the local market level along the rural-urban divide should be examined (Beverly and Neill, 2022). The latter effect might determine how futures values are transmitted to local markets.

By not directly including local agricultural production, we avoid potential problems related to simultaneity (in the price decomposition) and multicollinearity (in the nutrition-price analysis). Furthermore, maize production data at the necessary scale were not available for this research. Our analysis, therefore, might not clearly distinguish the impacts of food access from that of food availability on nutrition. In previous research, local food production is found to reduce stunting, especially for wealthy children (Grace et al., 2016). Disentangling food production and food price impacts on nutrition should be pursued in future research.

Our underlying nutrition and price data originate from different sources. The matching of households to the nearest market is based on the geolocations provided in the two data sources. Our market price data is limited; thus, the matches might not represent the in reality relevant market for each household. Nevertheless, infrastructure, market integration, and weather shocks might be comparable to the true market in many cases. Moreover, owing to confidentiality reasons, the household locations are shifted by up to 10 km, which adds further error to our geo-matching approach.

5.6 Conclusion

High and volatile staple food prices are often regarded as threats to food security. In particular, nonseasonal unexpected price volatility might reduce food access, as households might not have a chance to adjust their food production, purchases, storage, and subsistence behaviors accordingly. Climate change and related weather shocks can affect crop yields and, via market effects and related expectations, food prices. Increasingly integrated global value chains and trade relations cause the transmission of international price changes to local market levels.

Our decomposition reveals that futures volatility is a considerable driver of unexpected price volatility in local markets. This price transmission is evident across our methodological approaches. The Shapley value decomposition suggests simultaneous movements between volatility at international and local levels, but the impacts of futures drops (i.e., negative futures volatility) on local price volatility are stronger than those of futures spikes. The effect direction of weather shocks on unexpected price volatility are less clear.

We use futures volatility and, in some model specifications, weather shocks as instruments and fixed-effects decomposition as the first stage of a two-stage instrumental variable approach. We employ the predicted mean unexpected price volatility as the main variable of interest to investigate its effects on children's nutrition. In contrast to the directly calculated price variables, this volatility indicator is assumed free from simultaneity concerns related to linkages among food prices, food production, food purchases, and nutrition.

Unexpected nonseasonal price volatility (overall),and price spikes and drops (in particular) increase the occurrence of stunting in children and consistently decrease the underlying height-for-age z-score. The effects on stunting from predicted mean unexpected volatility are particularly large and significant for rural, agricultural, and poor households. Furthermore, being a twin, being a boy, and having parents with limited education increase the occurrence of stunting across subgroups. While higher volatility in the year before the survey appears to increase stunting, higher volatility around the time of birth is related to reduced stunting for nearly all subgroups. Potentially, higher volatility or price increases around the time of birth cause adjustments in storage and selling behaviors preventing stunting later on. Also, various households might benefit from higher prices with long-term positive consequences for nutrition. Alternatively, price volatility could also cause families to delay pregnancies or miscarriage (Grace et al., 2014). In this case, our results for the price effects around birth could be driven by households with generally lower risk of food insecurity. Predicted mean unexpected volatility before the survey is found to correlate with reduced diet diversity, most significantly and strongly for children below 2 years of age.

We complement existing research (i) by investigating price volatility drivers in a decomposition analysis using econometrics and ML tools, (ii) by employing a two-stage instrumental variable approach to account for endogeneity concerns and move toward a causal estimate of the effect of price volatility on nutrition, and (iii) by considering the heterogeneity in how subgroups are affected by different price indicators with respect to multiple nutrition indicators.

For indicators other than stunting and haz, price volatility effects appear small, insignificant, and less robust. These and effects related to price movements around the time of birth require further investigation. Nonetheless, our findings clearly suggest that price volatility can be transmitted from international futures volatility to local markets in SSA and that it increases stunting within the following year across household groups. Poor, rural, and agricultural households are affected the most, which indicates that also food-producing households can be net food buyers and that their children's nutrition might deteriorate because of higher and more volatile staple food prices, especially if the changes occur unexpectedly.

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5.8 Appendix

5.8.1 *A. Additional results price decomposition*

Table 5.6 Price decomposition regression results for different price indicators

	Price level	**General volatility**	**Unexpected volatility**	**Mean unexpected volatility**
Futures level	**0.26*****			
	(0.02)			
Mean temperature CS	**0.02*****	**0.01*****	**0.02*****	**0.02*****
	(0.00)	(0.00)	(0.00)	(0.00)
Total rainfall CS	**-0.06*****	-0.01	**-0.03****	**-0.02***
	(0.01)	(0.01)	(0.01)	(0.01)
Futures level: mean temp. CS	**-0.00***			
	(0.00)			
Futures level: total rain. CS	**0.05*****			
	(0.01)			
General futures volatility		**1.13*****		
		(0.10)		
General futures volatility: mean temp. CS		**-0.05*****		
		(0.00)		
General futures volatility: total rain. CS		**0.30*****		
		(0.06)		
Unexpected futures volatility			**0.36*****	
			(0.03)	
Unexpected futures volatility: mean temp. CS			**-0.02*****	
			(0.00)	
Unexpected futures volatility: total rain. CS			**0.12*****	
			(0.02)	
Mean unexpected futures volatility				**0.56*****
				(0.03)
Mean unexpected futures volatility: mean temp. CS				**-0.01*****
				(0.00)
Mean unexpected futures volatility: total rain. CS				**0.13*****
				(0.02)
Num. obs.	43027	42433	44008	42979
R^2 (full model)	0.84	0.42	0.47	0.53
R^2 (proj model)	0.01	0.01	0.01	0.01
Adj. R^2 (full model)	0.84	0.41	0.46	0.52
Adj. R^2 (proj model)	0.00	-0.01	-0.01	0.00
Num. groups: market	514	509	515	514
Num. groups: year	24	24	24	24
Num. groups: month	12	12	12	12

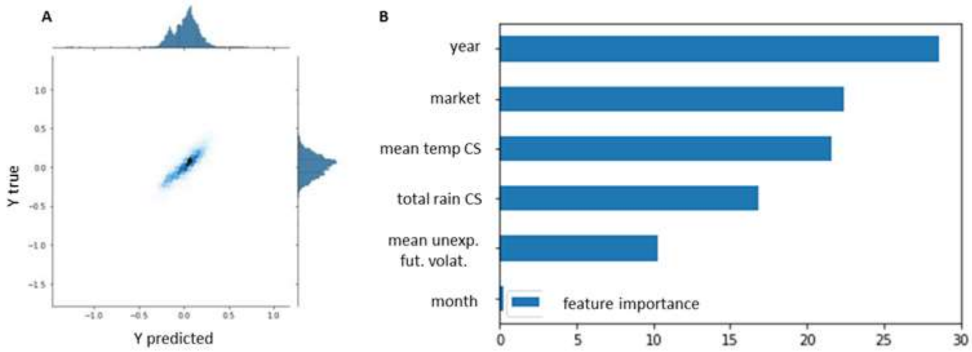

Figure 5.6 A: Distribution of mean unexpected price volatility (Y true) and its prediction (Y predicted) B: Feature importance

Figure 5.6 shows the distribution of true mean unexpected price volatility and its prediction for the CatboostRegressor (A). Both are nearly normally distributed and range between -0.5 and 0.5. Feature importance[20], calculated with default settings, indicates the influence of a change in the respective feature value on the average prediction value of the outcome variable. Feature values are normalized to sum up to 100. The feature importance values displayed in Figure 5.6B demonstrate, that predicted local market price volatility strongly depends on the year and the respective market. Local weather is also important, while a change in mean temperature has more influence on the predicted price volatility than a change in rainfall. For the average prediction value, futures volatility seems to be less important. The month appears to be least important for the prediction value, which is in line with expectations since we use the mean unexpected non-seasonal price volatility of which the monthly mean had been deducted as dependent variable. Underlying ranking modes might distort resulting feature importance values. We therefore focus on Shapley values in the following that also differentiate low-to-high feature values.

The RandomForestRegressor[21] achieves a score in the train split of R^2_{train}=0.99 and of R^2_{test}=0.95 in the test data split. The XGBRegressor[22] achieves R^2_{train}=0.52, R^2_{test}=0.50 and the LGBMRegressor[23] R_{train}^2=0.73,

[20] Calculated with catboosts get_feature_importance in default settings https://catboost.ai/en/docs/concepts/python-reference_catboostregressor_get_feature_importance

[21] https://scikit-learn.org/stable/modules/generated/sklearn.ensemble.RandomForestRegressor.html

[22] https://xgboost.readthedocs.io/en/stable/parameter.html

[23] https://lightgbm.readthedocs.io/en/latest/pythonapi/lightgbm.LGBMRegressor.html

R_{test}^2=0.69 for the same set of variables. In these models, markets were not captured as feature.

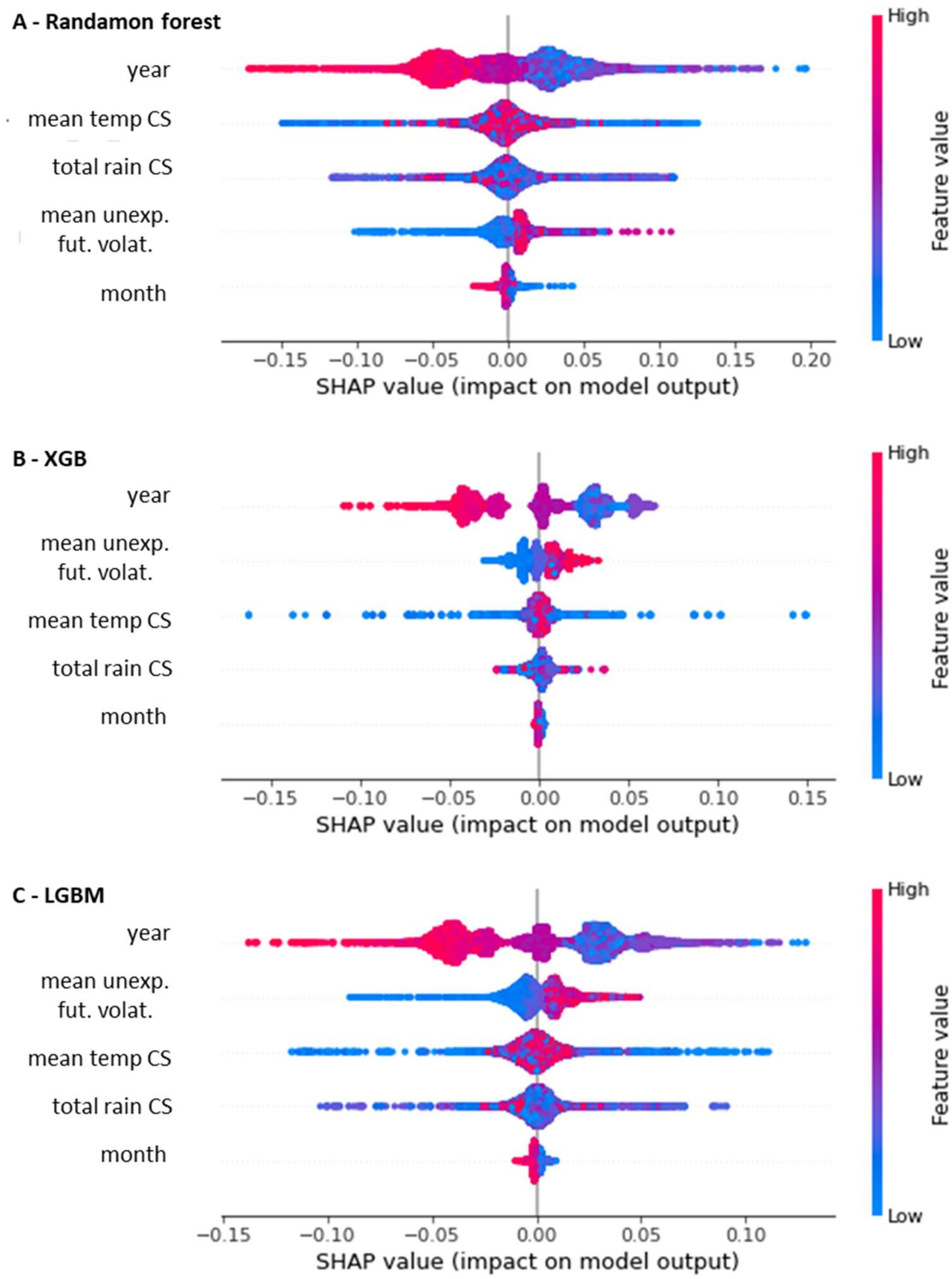

Figure 5.7 Shapley value decomposition for other ML models

5.8.2 *B. Further price indicators*

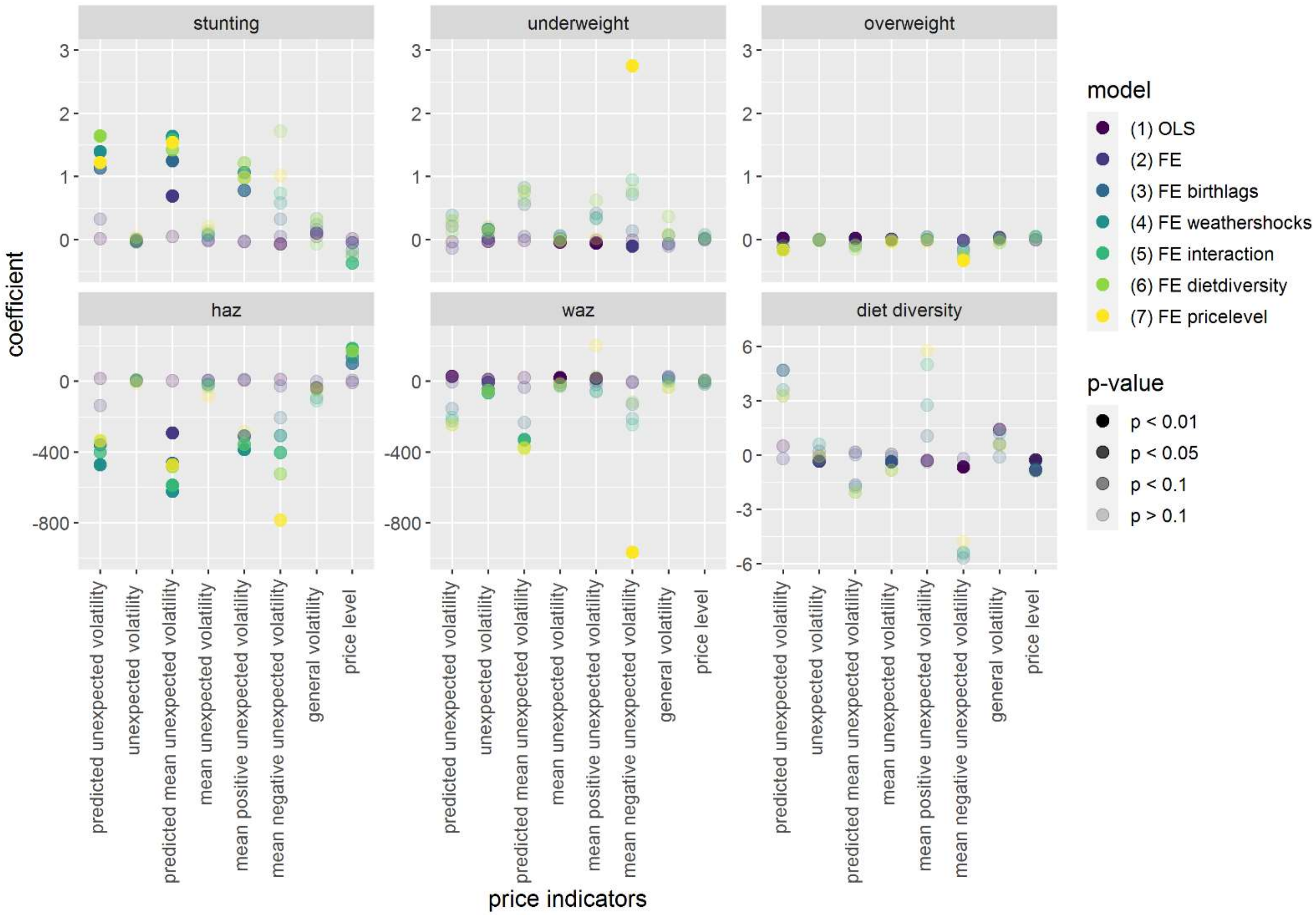

Figure 5.8 Multi-regression results of nutrition-price analysis including (predicted) unexpected volatility

Regression results underlying Figure 5.5 and Figure 5.8 can be accessed online under https://doi.org/10.22000/711.

Table 5.7 Regression results stunting – Predicted mean unexpected volatility (PMUV) model 5

Stunting	**Predicted mean unexpected volatility (PMUV)**							
	full	**rural**	**urban**	**poor**	**middle**	**rich**	**agriprod**	**foodcon**
Preceding year	**1.59****	**2.01***	0.86	**2.92****	2.01	**1.30***	**2.12***	0.42
	(0.48)	(0.78)	(0.68)	(0.95)	(1.38)	(0.62)	(0.96)	(0.87)
Postbirth	-0.19	**-0.28**$^{\cdot}$	0.12	-0.21	-0.26	-0.31	-0.23	0.31
	(0.15)	(0.17)	(0.38)	(0.17)	(0.22)	(0.19)	(0.22)	(0.56)
Prebirth	**-0.36***	**-0.30**$^{\cdot}$	-0.67	**-0.28**$^{\cdot}$	-0.06	**-0.56***	0.32	-0.96
	(0.18)	(0.16)	(0.41)	(0.16)	(0.27)	(0.23)	(0.26)	(0.72)
Urban	**-0.08*****			-0.01	0.00	**-0.12*****		
	(0.02)			(0.05)	(0.06)	(0.03)		
Poor	0.02	**0.03**$^{\cdot}$	-0.01				0.04	0.03
	(0.02)	(0.02)	(0.08)				(0.03)	(0.14)
Rich	-0.02	-0.01	**-0.10**$^{\cdot}$				-0.04	-0.12
	(0.02)	(0.03)	(0.05)				(0.04)	(0.10)
Male	**0.03*****	**0.03*****	**0.02**$^{\cdot}$	**0.03*****	**0.04****	**0.02**$^{\cdot}$	**0.04*****	**0.02**$^{\cdot}$
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Birth order	**0.01*****	**0.01*****	**0.01****	**0.01****	**0.01***	**0.01*****	0.01	**0.01***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.01)
Age mother	**-0.01*****	**-0.01*****	**-0.01*****	**-0.00*****	**-0.01***	**-0.01*****	**-0.00**$^{\cdot}$	**-0.01*****
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Mother no education	**0.13*****	**0.12****	**0.13*****	**0.33****	0.02	**0.12*****	-0.10	**0.11****
	(0.02)	(0.04)	(0.02)	(0.12)	(0.09)	(0.02)	(0.21)	(0.04)
Mother primary educ.	**0.12*****	**0.11****	**0.12*****	**0.32****	0.02	**0.11*****	-0.10	**0.10****
	(0.02)	(0.04)	(0.02)	(0.12)	(0.09)	(0.02)	(0.21)	(0.03)
Mother secondary educ.	**0.07*****	0.05	**0.06****	**0.27***	-0.02	**0.05****	-0.13	0.03
	(0.02)	(0.04)	(0.02)	(0.12)	(0.09)	(0.02)	(0.21)	(0.03)
Mother agri-occup.	0.00	-0.00	0.02	0.00	0.00	0.01		
	(0.01)	(0.01)	(0.02)	(0.01)	(0.02)	(0.01)		
Father no education	**0.08*****	**0.10*****	**0.06*****	0.05	0.07	**0.09*****	**0.14*****	**0.06****
	(0.02)	(0.02)	(0.02)	(0.04)	(0.05)	(0.02)	(0.04)	(0.02)
Father primary educ.	**0.06*****	**0.09*****	**0.04****	0.04	0.05	**0.05****	**0.13*****	**0.03**$^{\cdot}$
	(0.01)	(0.02)	(0.02)	(0.04)	(0.04)	(0.02)	(0.04)	(0.02)

Stunting	**Predicted mean unexpected volatility (PMUV)**							
	full	**rural**	**urban**	**poor**	**middle**	**rich**	**agriprod**	**foodcon**
Father secondary educ.	**0.04****	**0.07****	**0.02**$^{.}$	0.00	0.05	**0.04****	**0.10****	0.02
	(0.01)	(0.02)	(0.01)	(0.04)	(0.04)	(0.01)	(0.04)	(0.01)
Unfinished floor	**0.03*****	**0.02***	**0.04****	0.01	0.02	**0.04****	0.01	0.03
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.03)
Piped water	**0.05**$^{.}$	**0.09**$^{.}$	**0.04**$^{.}$	0.07	**0.22****	**0.03**$^{.}$	**0.28**$^{.}$	0.03
	(0.03)	(0.05)	(0.02)	(0.07)	(0.07)	(0.02)	(0.15)	(0.02)
Surface water	**0.06***	**0.09**$^{.}$	**0.09****	0.06	**0.22****	0.04	**0.28**$^{.}$	0.07
	(0.03)	(0.05)	(0.03)	(0.07)	(0.07)	(0.03)	(0.14)	(0.05)
Well water	0.04	0.09	0.03	0.06	**0.20****	0.03	**0.28***	0.03
	(0.03)	(0.06)	(0.02)	(0.07)	(0.06)	(0.02)	(0.14)	(0.02)
Height mother	**-0.00****	**-0.00***	**-0.00**$^{.}$	-0.00	**-0.00*****	**-0.00***	**-0.00*****	**-0.00*****
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Has livestock	**-0.02**$^{.}$	**-0.02***	**-0.02**$^{.}$	**-0.02**$^{.}$	**-0.06****	0.00		
	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.01)		
Has agri-land	**0.02****	**0.02**$^{.}$	0.01	-0.01	**0.07****	0.01		
	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.01)		
Twin	**0.09*****	**0.11*****	**0.04**$^{.}$	**0.10*****	**0.12***	**0.06***	**0.13*****	0.01
	(0.02)	(0.03)	(0.02)	(0.03)	(0.05)	(0.03)	(0.03)	(0.03)
Age in months	**0.01*****	**0.01*****	**0.00**$^{.}$	**0.01*****	**0.01****	**0.00***	**0.01***	**0.00**$^{.}$
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Distance househ.-market	0.00	0.00	-0.00	0.00	-0.00	-0.00	**0.00***	-0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Total rainfall CS	-0.00	0.06	-0.16	-0.06	-0.08	0.06	**0.37**$^{.}$	-0.06
	(0.13)	(0.13)	(0.14)	(0.19)	(0.19)	(0.14)	(0.20)	(0.17)
Mean temperature CS	**-0.06****	**-0.08***	-0.03	**-0.13****	-0.10	-0.03	-0.03	-0.07
	(0.02)	(0.04)	(0.03)	(0.04)	(0.06)	(0.03)	(0.05)	(0.06)
Preceding year:Poor	-0.01	-0.01	-0.31				-0.20	0.31
	(0.11)	(0.11)	(0.45)				(0.20)	(0.76)
Preceding year:Rich	**0.25***	**0.27***	0.09				0.17	0.59
	(0.11)	(0.13)	(0.31)				(0.22)	(0.64)
Postbirth:Poor	0.02	0.04	-0.10				0.25	-0.28
	(0.12)	(0.13)	(0.44)				(0.21)	(0.57)
Postbirth:Rich	-0.18	-0.14	-0.27				0.18	-0.57
	(0.13)	(0.16)	(0.28)				(0.26)	(0.47)
Prebirth:Poor	0.06	0.04	0.20				-0.29	0.32
	(0.13)	(0.13)	(0.41)				(0.26)	(0.73)
Prebirth:Rich	-0.01	-0.05	0.41				0.05	0.75

Stunting	Predicted mean unexpected volatility (PMUV)							
	full	**rural**	**urban**	**poor**	**middle**	**rich**	**agriprod**	**foodcon**
	(0.16)	(0.21)	(0.25)				(0.35)	(0.51)
Preceding year:Urban	-0.21			0.11	-0.20	**-0.25***		
	(0.14)			(0.34)	(0.34)	(0.12)		
Postbirth:Urban	0.10			0.07	0.14	0.14		
	(0.14)			(0.26)	(0.32)	(0.14)		
Prebirth:Urban	0.17			-0.02	0.03	0.24		
	(0.16)			(0.34)	(0.35)	(0.18)		
Num. obs.	35127	24865	10262	15085	6930	13112	9835	5344
R^2 (full model)	0.12	0.09	0.15	0.08	0.11	0.14	0.11	0.16
R^2 (proj model)	0.05	0.03	0.04	0.02	0.03	0.04	0.05	0.04
Adj. R^2 (full model)	0.11	0.07	0.13	0.06	0.07	0.12	0.08	0.12
Adj. R^2 (proj model)	0.04	0.02	0.02	-0.00	-0.01	0.02	0.02	-0.00
Num. groups: market	293	279	209	264	251	258	235	173
Num. groups: year	9	9	9	9	9	9	9	9
Num. groups: birth year	16	16	16	16	16	16	16	16

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Table 5.8 Regression results diet diversity – PMUV, positive and negative MUV model 4

Diet diversity	**PMUV**			**Positive MUV**			**Negative MUV**		
	full	**young**	**old**	**full**	**young**	**old**	**full**	**young**	**old**
Preceding year	-1.76	1.88	-2.60	2.76	**98.39**$^{\cdot}$	2.23	-5.37	-55.62	-6.00
	(2.88)	(29.35)	(2.85)	(2.66)	(52.05)	(2.67)	(4.07)	(47.39)	(4.20)
Postbirth	**1.67***	**71.17**$^{\cdot}$	**2.19****	-0.24	29.48	0.13	-0.82	**-259.38****	-1.15
	(0.71)	(40.83)	(0.73)	(0.74)	(30.16)	(0.70)	(0.95)	(48.61)	(1.02)
Prebirth	0.90	-63.40	**1.36***	**-1.58***	58.98	**-1.28**$^{\cdot}$	-2.16	-45.96	-2.10
	(0.78)	(67.62)	(0.65)	(0.68)	(49.59)	(0.67)	(1.93)	(59.19)	(1.85)
Urban	**0.10**$^{\cdot}$	-0.63	**0.10**$^{\cdot}$	0.01	-0.81	0.02	**0.21***	**-2.34**$^{\cdot}$	**0.20***
	(0.06)	(0.51)	(0.06)	(0.08)	(0.83)	(0.08)	(0.09)	(1.00)	(0.09)
Poor	**-0.16****	0.33	**-0.17****	-0.05	-0.24	-0.06	**-0.19**$^{\cdot}$	-0.76	**-0.21***
	(0.06)	(0.43)	(0.06)	(0.08)	(0.77)	(0.08)	(0.10)	(1.03)	(0.10)
Rich	0.08	0.27	0.08	**0.10**$^{\cdot}$	-0.28	**0.11**$^{\cdot}$	0.03	**-2.26**$^{\cdot}$	0.02
	(0.05)	(0.58)	(0.05)	(0.06)	(0.91)	(0.06)	(0.11)	(1.06)	(0.12)
Male	-0.02	**-0.58**$^{\cdot}$	-0.02	-0.03	-0.80	-0.03	-0.06	0.78	-0.06
	(0.03)	(0.33)	(0.04)	(0.05)	(0.71)	(0.05)	(0.06)	(0.72)	(0.06)
Birth order	-0.01	0.02	-0.01	0.01	**0.40***	0.01	**-0.06***	**0.55**$^{\cdot}$	**-0.06***
	(0.01)	(0.11)	(0.01)	(0.02)	(0.20)	(0.02)	(0.02)	(0.20)	(0.02)
Age mother	0.01	-0.00	0.01	-0.00	**-0.15***	0.00	0.02	-0.05	0.02
	(0.01)	(0.04)	(0.01)	(0.01)	(0.07)	(0.01)	(0.01)	(0.07)	(0.01)
Mother no education	**-0.34**$^{\cdot}$	0.11	**-0.34**$^{\cdot}$	-0.10	-0.33	-0.08	-0.15	-0.12	-0.13
	(0.19)	(1.31)	(0.19)	(0.23)	(2.97)	(0.24)	(0.29)	(0.68)	(0.30)
Mother primary educ.	-0.29	-0.27	-0.29	0.04	-2.35	0.06	-0.16	**2.51***	-0.15
	(0.19)	(1.07)	(0.19)	(0.22)	(2.96)	(0.23)	(0.28)	(0.57)	(0.29)
Mother secondary educ.	-0.15	0.24	-0.15	0.14	-1.72	0.15	-0.08	**8.63*****	-0.07
	(0.19)	(1.04)	(0.20)	(0.24)	(2.68)	(0.25)	(0.27)	(0.88)	(0.28)
Mother agri-occup.	0.06	0.78	0.06	-0.06	0.37	-0.06	0.08	**2.70****	0.07
	(0.07)	(0.59)	(0.07)	(0.10)	(0.79)	(0.10)	(0.15)	(0.51)	(0.15)
Father no education	**-0.17**$^{\cdot}$	-0.06	**-0.18**$^{\cdot}$	-0.18	0.18	-0.17	-0.02	**4.99****	-0.03
	(0.09)	(0.88)	(0.09)	(0.15)	(2.97)	(0.16)	(0.14)	(1.00)	(0.14)
Father primary education	-0.14	0.15	-0.14	**-0.26**$^{\cdot}$	0.91	-0.25	0.05	**5.78****	0.03
	(0.09)	(0.73)	(0.09)	(0.15)	(2.82)	(0.16)	(0.14)	(1.22)	(0.14)
Father secondary education	-0.11	0.47	-0.12	-0.14	1.17	-0.14	-0.06	**6.30****	-0.07
	(0.09)	(0.83)	(0.09)	(0.16)	(2.70)	(0.17)	(0.13)	(1.12)	(0.14)
Unfinished floor	-0.02	-0.60	-0.02	-0.00	0.40	0.01	-0.14	-0.26	-0.14
	(0.06)	(0.57)	(0.06)	(0.08)	(0.64)	(0.08)	(0.09)	(0.59)	(0.09)
Piped water	-0.18		-0.19	0.06		0.06	-0.25		-0.27
	(0.16)		(0.16)	(0.29)		(0.29)	(0.16)		(0.16)
Surface water	-0.19	-0.75	-0.18	0.01	0.57	0.03	-0.17	**-3.45***	-0.17

Diet diversity	PMUV			Positive MUV			Negative MUV		
	full	**young**	**old**	**full**	**young**	**old**	**full**	**young**	**old**
	(0.14)	(0.49)	(0.15)	(0.26)	(0.79)	(0.26)	(0.17)	(0.92)	(0.17)
Well water	-0.16	-0.59	-0.15	0.12	0.41	0.14	-0.11	**-1.98***	-0.11
	(0.15)	(0.76)	(0.15)	(0.27)	(0.98)	(0.27)	(0.16)	(0.70)	(0.16)
Mother height	0.00	0.01	0.00	0.00	0.01	0.00	-0.00	**0.02***	-0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.01)	(0.00)
Has livestock	**0.09**$^{\cdot}$	0.28	0.09	0.12	-0.29	0.11	**0.18****	0.75	**0.18****
	(0.05)	(0.49)	(0.06)	(0.10)	(0.62)	(0.10)	(0.06)	(0.63)	(0.06)
Has agri-land	-0.03	0.09	-0.03	0.02	0.01	0.03	-0.09	**-2.28***	-0.09
	(0.04)	(0.56)	(0.04)	(0.06)	(0.58)	(0.07)	(0.06)	(0.73)	(0.06)
Twin	0.01	-0.46	0.02	-0.10	1.74	-0.09	0.31	**-1.53**$^{\cdot}$	0.33
	(0.13)	(0.93)	(0.14)	(0.18)	(3.08)	(0.18)	(0.22)	(0.65)	(0.24)
Age in months	0.01			**0.02****			0.01		
	(0.01)			(0.01)			(0.01)		
Distance househ.-market	0.00	-0.00	0.00	-0.00	-0.00	-0.00	-0.00	**0.00**$^{\cdot}$	-0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Total rainfall CS	-0.91	-25.09	-0.96	0.18	14.29	0.16	-0.96	**-241.45**$^{\cdot}$	-1.01
	(0.62)	(19.10)	(0.61)	(1.04)	(32.14)	(0.97)	(1.30)	(98.77)	(1.32)
Mean temperature CS	0.17	0.06	0.18	0.37	7.74	0.37	0.44	5.83	0.42
	(0.26)	(2.44)	(0.25)	(0.30)	(6.36)	(0.27)	(0.51)	(3.60)	(0.51)
Num. obs.	14598	206	14392	7305	126	7179	4754	68	4686
R^2 (full model)	0.20	0.65	0.20	0.25	0.66	0.24	0.22	0.94	0.22
R^2 (proj model)	0.01	0.19	0.01	0.01	0.27	0.01	0.02	0.84	0.02
Adj. R^2 (full model)	0.18	0.24	0.18	0.22	0.13	0.22	0.19	-0.00	0.18
Adj. R^2 (proj model)	-0.01	-0.78	-0.01	-0.02	-0.87	-0.02	-0.02	-1.67	-0.02
Num. groups: market	255	74	253	179	43	177	144	29	143
Num. groups: year	8	7	8	7	6	7	8	6	8
Num. groups: birth_year	16	9	16	15	7	15	16	8	16

5.8.3 *C. Data coverage for different diet indicators*

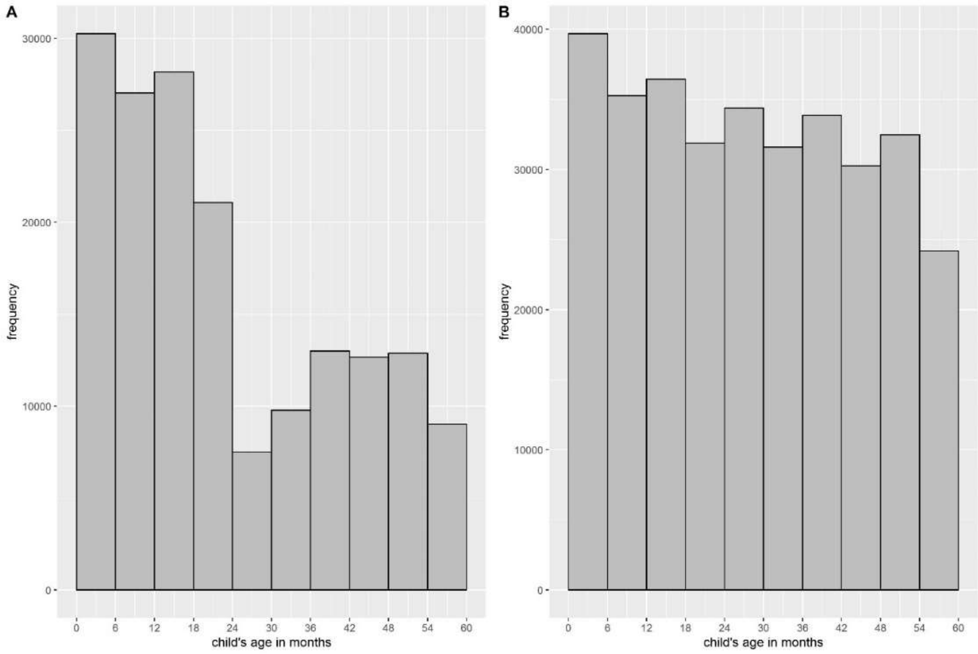

Figure 5.9 Histogram of child's age in months excluding non-available data for (A) diet diversity and (B) haz.