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True Cost Accounting for Food application: Environmental, social and health impacts of bread

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HIGHLIGHTS

- Introduces a comprehensive TCAF framework at the product level.
- Expands TCAF with indicators for biodiversity and dietary health impacts.
- Compares conventional, extensive, and organic wheat farming systems.
- Biodiversity and health impacts are key cost drivers of bread true costs.

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ABSTRACT

True Cost Accounting for Food (TCAF) has been put forward as a holistic approach for food system transformation. However, product level case studies are still scarce. This study proposes a comprehensive approach to TCAF at the product level. We examine bread produced and consumed in Switzerland, evaluating three production methods (conventional, extensive, and organic farming) and two types of wheat (refined and whole). By carrying out a life cycle assessment (LCA) supplemented by methods of accounting for biodiversity, livelihoods and health, this research aims to provide a broad assessment of the impacts of bread production. The study expands current TCAF approaches to include more indicators at the product level, emphasizing the importance of biodiversity and dietary-risk-related health impacts. The findings reveal significant cost differences among the three farming practices. The highest costs are attributed to biodiversity and health impacts. Consumption of wholegrain wheat is beneficial to health because of the underconsumption of wholegrain cereals in the typical Swiss diet.

1. Introduction

Food and agricultural systems support the livelihoods of billions of people and have helped reduce the proportion of undernourished individuals from 12.7% to 9.7% over the last twenty years (Ritchie et al., 1970). However, research has shown that most agri-food systems contribute significantly to exceeding planetary limits, while exacerbating existing inequalities (Campbell et al., 2017). The transformation of the agri-food system has therefore been widely recognized as necessary to meet the United Nations' Agenda 2030 goals of reconciling growth in food demand with reducing of environmental, social and health impacts, while coping with increasing climatic, economic and political shocks (Independent Group of Scientists appointed by the Secretary-General, 2019).

True Cost Accounting for Food (TCAF), which involves measuring social, environmental and health impacts in monetary terms, has been presented as a holistic approach to transforming food systems, both internationally and nationally (Baker et al., 2020; Gemmill-Herren et al., 2021). Many of the costs and benefits associated with food systems are not reflected in market prices. This has been identified as a major contributor to the systems' unsustainability, resulting in

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distorted incentives for market participants (Hendriks et al., 2023). The underlying rationale is that by internalizing the externalities of food systems, economic incentives would shift towards the production and consumption of food with reduced environmental, social, and health impacts. Ultimately, this would decrease the societal costs imposed by current food systems, considering impacts of different nature. TCAF is still a recent field in academia: to date, three studies provide the true cost of the global food system, with results ranging from 12 trillion USD (Food and Land Use Coalition, 2019; FAO, 2023) to 29 trillion USD (Hendriks et al., 2023), as well as studies providing national estimates (FAO, 2024; Perotti, 2020; Sustainable Food Trust, 2019). However, product level TCAF studies are still scarce (Nature Food, 2020; Michalke et al., 2023; Bellon et al., 2024) and there is no commonly agreed standard. Peer-reviewed articles have focused mainly on the environmental impact of food (Michalke et al., 2023), to the detriment of social and health aspects, neglecting impacts such as pesticide ingestion and excessive working hours of farmers.

We aim to help fill this gap of comprehensive product level TCAF by studying the true cost of one of the main consumed crops at the global level, i.e. wheat. The latter is the world's third most widely grown crop in terms of area and production (FAO, 2022) and provides 20% of the world's total food calories and protein intake (Shiferaw et al., 2013). Most of the wheat produced is used to make bread, one of the most universal foods, with an average consumption of between 59 and 70 kg per capita per year (Carocho et al., 2020). Bread can be produced in a variety of ways, leading to heterogeneous impacts on sustainability and health depending on farming practices and consumer eating habits (Weegels, 2019; Serra-Majem and Bautista-Castaño, 2015). By way of illustration, due to the refining process, wholegrain breads require less inputs (e.g., land, energy) and offer a variety of health benefits, including fiber, vitamins and minerals, contributing to digestive health and well-being (Serra-Majem and Bautista-Castaño, 2015), compared to breads made with refined flours (Serra-Majem and Bautista-Castaño, 2015; Schlesinger et al., 2019). According to the Global Burden of Disease study, chronic underconsumption of wholegrain cereals led to 210,000 avoidable deaths and 3.5 million disability-adjusted life years (DALYs) in EU member states in 2019 (GBD 2017 Risk Factor Collaborators, 2019).

Our research involves assessing the TCAF of different types of bread, in relation to its multiple sustainability and health issues using secondary data. Our case study focuses on breads produced and consumed in a high-income country, namely Switzerland, considering three agricultural practices (conventional, extensive and organic) and two types of bread (breads made from refined and wholegrain flours). Our TCAF method aims to cover the following impact categories: environment, biodiversity, livelihoods, public spendings and human health. Life cycle assessment (LCA) was used to cover environmental impacts; land use eco-costs were used for biodiversity; human toxicity costs were used to assess pesticide ingestion impacts; disability-adjusted life years (DALYs) were used to assess dietary-risk-related health impacts; agricultural subsidies were used to measure public spending; and overworked hours were used to measure the impact on livelihoods. Finally, we monetized the impacts based on the monetization factors of the True Price Foundation (True Price Foundation, 2023).

2. Materials, methods, and calculations

2.1. Scope and frame

2.1.1. Goals and scope

The study aims to assess the impact of a universally consumed food product, bread, using a true cost accounting methodology, which will enable us to communicate on the impacts and true costs of food to a large audience. Key steps in the TCAF include quantifying the impacts per functional unit and multiplying them by monetization factors to convert them into monetary terms. The literature provides several methods and frameworks for assessing the true cost of food at different scope (FAO et al.; True Cost Initiative and TMG Soil more impacts, 2022; The Rockerfeller Foundation, 2021), but none has become a commonly agreed standard. In this case study, we will assess the impact of whole and refined bread produced through conventional, extensive and organic farming, on five impact categories: human health, environment, biodiversity, livelihoods and public spendings.

2.1.2. System boundaries

The scope of the system follows a farm-to-fork analysis for bread produced in Switzerland, which includes: primary production, manufacturing, retail, consumption and waste. The downstream non-food value chain is excluded from our scope, similarly to the FAO methodology (FAO et al.). A typical Swiss bread recipe was used to define the quantities of ingredients for 1 kg of bread: flour (0.59 kg), water (0.38 kg), yeast (0.02 kg) and salt (0.01 kg) (Pain Suisse, 2023). Three farming systems were considered for primary production: conventional, extensive, and organic farming, which account for 64%, 29%, and 7%, respectively, of Swiss wheat production (OFS, 2024a). All farming systems have specific requirements, especially regarding the use of inputs (see Table 4). Conventional farming is subject to maximum residue limit (MRL) regulations, which express the maximum concentration of a pesticide residue legally permitted in food and feed. Extensive farming refers to the Swiss "extenso" label, which bans chemical fungicides, insecticides and growth regulators, a compromise between conventional and organic farming. Regarding inputs, organic farming bans synthetic chemical substances, including fertilizers and pesticides, as well as herbicides (Agridea, 2025).

In Switzerland, food consumption across the value chain results in 2.8 million tons of food loss (at production level) and waste (at consumer level) per year, representing 37% of agricultural production (EAER and FOAG, 2021) and 20% of the climate impacts of food consumption (Beretta et al., 2017). It is therefore essential to consider the impacts of waste as part of a TCAF methodology across all indicators. We include food waste and losses per kg of bread consumed, for a total of 55% across production, processing, gastronomy, retail, and households (Beretta and Hellweg, 2019).

2.1.3. Functional unit

Our functional unit is defined as the production of 1 kg of bread. However, given that bread is the most wasted food item in Switzerland (Beretta and Hellweg, 2019), the impact of producing 1 kg of bread differs significantly from the impact of consuming 1 kg. Therefore, we have incorporated both production-based and consumption-based perspectives to account for the waste dynamics across our five impact categories.

2.2. Impacts, indicators and metrics

The following section presents the categories, definitions, rationales, indicators and datasets for each impact. Priority was given to the most relevant impacts, taking into account data availability, cross-compatibility of datasets and feasibility.

2.2.1. Human health

Diet related diseases are non-communicable diseases (NCD) such as coronary heart disease, stroke, cancers and type 2 diabetes (Willett et al., 2019) which are caused by unbalanced diets (DFI, 2017). These diseases are caused by over- or underconsumption of food groups. At the global level, unhealthy diets are the largest burden of disease and present a greater risk to morbidity and mortality than does alcohol, drug, tobacco, and unsafe sex combined (Willett et al., 2019; Haddad et al., 2016). Widespread undernutrition persists, with approximately 735 million people experiencing hunger in 2022 (FAO et al.), while the rates of overweight, obesity, and non-communicable diseases continue to rise (Willett et al., 2019). The current Swiss diet is unbalanced and

Table 1
Summary of LCA processes, databases and scope considered in the study.

Process	LCA process	Database	Scope
Wheat production	Wheat production, Swiss integrated production, intensive | wheat grain, Swiss integrated production | Cutoff, U	Ecoinvent	CH
	Wheat production, Swiss integrated production, extensive | wheat grain, Swiss integrated production | Cutoff, U	Ecoinvent	CH
	Wheat production, organic | wheat grain, organic | Cutoff, U	Ecoinvent	CH
Milling	Wheat grain processing, dry milling | wheat flour | Cutoff, U	Ecoinvent	GLO
Baking	Oven baking, industrial, 1 kg of oven-baked product, for cooking	Agribalyse	FR
Ingredients	Market for tap water | tap water | Cutoff, U	Ecoinvent	CH
	Baker's yeast, dehydrated, processed in FR | Ambient (long) | Paper | No preparation | at consumer	Agribalyse	FR
	Market for salt | salt | Cutoff, U	Ecoinvent	GLO

Table 2
Overview of impacts considered, associated indicators, valuation method, monetization methods converted to CHF and original source of monetization factors. Based on the True Price Foundation (True Price Foundation, 2023), we define the cost of restoration as "the cost of returning people's health, wealth, status, capabilities or environmental stocks and qualities to the state they would have been in the absence of the social and environmental damage associated with an impact", and the cost of compensation as "the cost of compensating affected people for the economic and/or non-economic damage caused by the social and environmental impacts of the production or consumption of a product". In the literature, this cost is also referred to as the "cost of damage". Finally, the prevention cost is "the cost that would be incurred in the future to avoid or prevent the recurrence of the identified social and environmental impacts of a product".

Impacts	Indicators	Valuation methods	Monetization methods	Monetization factors	Monetization factors original source
Global warming	kg CO_2-eq	LCA	restoration	0.1672 CHF/kg CO_2-eq	True Price (True Price Foundation, 2023)
Water consumption	m3	LCA	restoration	1.3645 CHF/m3	True Price (True Price Foundation, 2023)
Freshwater eutrophication	kg P-eq	LCA	restoration and compensation	214.4167 CHF/kg P-eq	True Price (True Price Foundation, 2023)
Marine eutrophication	kg N-eq	LCA	restoration and compensation	14.8758 CHF/kg N-eq	True Price (True Price Foundation, 2023)
Terrestrial acidification	kg SO_2-eq	LCA	compensation	4.9449 CHF/kg SO_2-eq	True Price (True Price Foundation, 2023)
Terrestrial ecotoxicity	kg 1,4DCB-eq	LCA	compensation	0.0003 CHF/kg 1,4DCB-eq	True Price (True Price Foundation, 2023)
Freshwater ecotoxicity	kg 1,4DCB-eq	LCA	compensation	0.0428 CHF/kg 1,4DCB-eq	True Price (True Price Foundation, 2023)
Marine ecotoxicity	kg 1,4DCB-eq	LCA	compensation	0.0019 CHF/kg 1,4DCB-eq	True Price (True Price Foundation, 2023)
Biodiversity	species richness	Eco-costs (Sustainability Impact Metrics)	prevention	6.156 CHF/m2 for a biodiversity factor of 1	Sustainability Impact Metrics methodology (Sustainability Impact Metrics, 2024)
Pesticide impact (ingestion)	DALYs	I-eco-costs (Sustainability Impact Metrics)	restoration	94789.4132 CHF/DALYs	TCA Handbook (True Cost Initiative and TMG Soil more impacts, 2022)
Impact via diet (ingestion)	DALYs	own methodology	restoration	94789.4132 CHF/DALYs	TCA Handbook (True Cost Initiative and TMG Soil more impacts, 2022)
Overworked hours	overworked hours	own methodology	compensation	18.991 CHF/overworked hours	Recommended brut salary of farm employee (USP et al., 2023) divided by maximum worked hours by Swiss law (Assemblée fédérale de la Confédération suisse, 1964)
Subsidies	CHF	own methodology	own methodology	own methodology	Swiss Federal Statistical Office (OFS, 2024a) and annual reports on agriculture (OFAG, 2024)

unhealthy (OSAV, 2022), mirroring trends observed in other European countries (Willett et al., 2019). Bodyweight is a recognized health indicator for non-communicable diseases (NCDs) (DFI, 2017), with 42% of the Swiss population being overweight (DFI, 2017; Fesenfeld et al., 2023). Beyond individual health impacts, NCDs account for 80% of the costs in the Swiss health system, amounting to CHF 51.7 billion (DFI, 2017; Barjolle et al., 2023). As there are several measures of impact on human health, the DALYs were chosen because of the availability of the corresponding monetization factors. DALYs are the sum of years lived with disability (YLDs) and years of life lost due to premature mortality (YLLs) (Devleesschauwer et al., 2014).

Pesticides are used in agriculture to protect crops and guarantee yields. Beyond biodiversity loss and environmental impacts, pesticides cause health issues through occupational, environmental and consumer exposure (European Environment Agency, 2023). Presumed links have been established between exposure to pesticides and increased risk of chronic diseases, which include various types of cancers, neurological disorders (e.g. Parkinson's and Alzheimer's diseases), cardiovascular diseases, development delays in children, effects on infertility, as well as cognitive and respiratory health impairments (European Environment Agency, 2023). In France, Parkinson's disease and non-Hodgkin lymphoma have been recognized as occupational diseases for farmers (Deprost et al., 2018). Due to limited data availability and monetization factors, this case study only considers the impact of pesticide ingestion on consumers. The health indicator considered at the consumer level is the number of DALYs per kg of pesticide.

2.2.2. Environment

Global warming is defined as the long-term warming of the planet's overall temperature. Human-induced global warming is driven by high emitting activities such as fossil fuels burning, livestock raising, and land use change, resulting in very serious threats. The food and agriculture system is responsible for more than a third of the global anthropogenic emissions (Crippa et al., 2021). The global warming indicator used in this study considers the emissions and global warming potential of the CO_2, N_2O and CH_4 expressed in CO_2 equivalent, assessed through the ReCiPe method (Huijbregts et al., 2016).

Water consumption can be defined as the use of water in such a way that it is evaporated, incorporated into products, transferred to other watersheds or discharged into the sea. It is thus no longer available in the watershed of origin for humans and ecosystems (Huijbregts et al., 2016; Falkenmark and Rockstrom, 2004). Water resources are under increasing pressure from population growth and rising food demand, with agricultural production accounting for the bulk of the world's freshwater consumption (Pfister et al., 2011). Water consumption is expressed in m^3 in the ReCiPe method (Huijbregts et al., 2016).

Terrestrial acidification occurs when soil acidity deviates detrimentally from this optimal acidity level of plant species (Huijbregts et al., 2016). On farmland, the main causes of soil acidification are the application of ammonium- and urea-based fertilizers, elemental sulfur-based fertilizers and legume growth (Goulding, 2016). Acidification leads to the deterioration of forests and surface waters, particularly in areas with poor soil quality (Pawlowski, 1997). The terrestrial acidification indicator accounts for the atmospheric fate and soil deposition of NO_x, NH_3 and SO_2, and is expressed in kg SO_2-eq under the ReCiPe method (Huijbregts et al., 2016).

Freshwater and marine eutrophication can be defined as the enrichment of inland and coastal waters with anthropogenically-driven inputs of nitrogen (N) and phosphorus (P) (Withers et al., 2014). Changes in nutrients lead to the proliferation of algae and aquatic weeds, which affect fish populations (Withers et al., 2014) and ultimately leading to a relative loss of species (Truhaut, 1977). Nitrogen and phosphorus loads from agriculture are one of the main factors in eutrophication (Withers et al., 2014). Under the ReCiPe method, freshwater eutrophication is expressed in kg P-eq and marine eutrophication in kg N-eq (Huijbregts et al., 2016).

Freshwater, marine and terrestrial ecotoxicity refers to the potential of biological, chemical or physical stressors to affect ecosystems (Truhaut, 1977). The contamination of ecosystems by toxic chemicals from human activities has become a global problem, with millions of tons of potentially toxic chemicals entering the environment every year (Fantke et al., 2018). Many of these chemical, such as pesticides, produce toxic metabolites that have harmful effects on living organisms and are liable to bioaccumulate and biomagnify (Fantke et al., 2018). In the ReCiPe method, the ecotoxicity indicators on freshwater, marine and terrestrial ecosystems account for the environmental persistence, accumulation and toxicity of a chemical (Huijbregts et al., 2016). It is expressed in kg 1,4-dichlorobenzene equivalents (1,4DCB-eq) (Huijbregts et al., 2016).

2.2.3. Biodiversity

Biodiversity can be defined as "species, genetic, and ecosystem diversity in an area, sometimes including associated abiotic components" (Swingland, 2001). Biodiversity contributes to humanity through a wide range of services, including habitat creation, human and animal nutrition, pollination, soil protection and the regulation of air quality, climate and ocean acidification (IPBES, 2019). However, biodiversity is facing irreversible impacts and extinction (Mace et al., 2014). Over the last 50 years, wild animal populations have declined by 73% (WWF, 2024). The main drivers of biodiversity loss are changes in land and sea use, direct exploitation of organisms, climate change, pollution and invasive species (IPBES, 2019). The most widespread type of land use change is agricultural expansion, with more than a third of the earth's surface devoted to crops or livestock raising (IPBES, 2019). No LCA method exhaustively takes into account all the dimensions of biodiversity (Damiani et al., 2023) due to its complexity involving species density, richness and diversity. Given the availability of data and the existing true cost methodology (Sustainability Impact Metrics, 2024), we use the species richness metric.

2.2.4. Livelihoods

Most of the livelihood indicators developed in the TCAF studies address issues specific to agricultural production contexts that are not relevant in Switzerland, such as child or forced labor. However, recent studies and demonstrations indicate that farmers in Switzerland are inadequately compensated for their substantial contributions to society. To address this, we have incorporated a "overworked hours" metric that captures two interconnected challenges: excessive working hours, which farmers reported as the second most significant disadvantage, and low wages, which farmers reported as the fourth most significant drawback (OFAG, 2022). Although further indicators could be incorporated, such as gender disparities or unpaid work by family members, the availability and relevance of the data led us to focus solely on overworked hours. The first and third disadvantages reported by farmers refer to low self-esteem, including the lack of recognition for their work, as well as the numerous prescriptions and changes in framework conditions (OFAG, 2022). Farm workers face increasing economic pressure, and the suicide rate among farmers is higher than among non-farmers (Steck et al., 2020).

Overworked working hours are defined as hours worked in excess of the legal working week. In Switzerland, farmers work an average of 66 h per week (OFS, 2023). Overtime (beyond the 50 h per week set by Swiss law) should be remunerated, to enable farmers to hire additional farm workers to manage the excess workload.

2.2.5. Public spendings

Subsidies are defined as incentives provided by government to support, through monetary or other aid, agricultural and food businesses. Global subsidies to agricultural producers are estimated at around $540 billion a year, but these costs are not reflected in food prices (UNEP et al., 2021). Therefore, subsidies play a key role in shaping food and farming systems, but they are a double-edged sword. On the one hand, subsidies can support agricultural production to improve food security, food self-sufficiency, as well as farmers' incomes and well-being. On the other hand, subsidies can lead to distorted incentives with unintended consequences, such as supporting practices that are unsustainable biodiversity, water, or soil quality. According to the United Nations (UNEP et al., 2021), 87% of current support schemes are "often inefficient and inequitable, distorting food prices, harming people's health and degrading the environment". In our study, subsidies refer to government payments to agricultural producers expressed in Swiss francs (CHF), but exclude other types of support. Data were collected and derived from the Swiss Federal Statistical Office (OFS, 2024a) and the annual reports on agriculture (OFAG, 2024).

2.3. Monetization methods

Monetization involves converting a measure or impact into monetary terms. For each indicator, we have identified an appropriate monetization approach from the range of possible options.

2.3.1. Environmental costs using LCA

For LCA-based indicators, we have combined a life cycle impact assessment (LCIA) method, namely ReCiPe (Huijbregts et al., 2016), with cost factors to monetize impacts according to Eq. (1). Table 1 summarizes the LCA processes, databases and scope considered.

$$TC_{i,j} = I_{i,j} \cdot MF_{i,j} \tag{1}$$

With:

$TC_{i,j}$: true cost of product i for metric j;

$I_{i,j}$: impact of product i for metric j;
$MF_{i,j}$: monetization factor of product i for metric j;

ReCiPe was chosen among other options due to the better match with our LCA inventory, which was based on Ecoinvent and Agribalyse. Monetization factors were based on the True Price Foundation report (True Price Foundation, 2023).

2.3.2. Biodiversity loss

Biodiversity loss is often overlooked in LCAs, except when it pertains to land use changes or pollutant releases. Nevertheless, it is a key performance indicator for comparing the sustainability of agricultural practices and, consequently, the true cost of food (Nemecek et al., 2023). It is important to note that incorporating all aspects of biodiversity into a single LCA method is not feasible (Damiani et al., 2023). Given the available data and the existing true cost method (Sustainability Impact Metrics, 2024), we use the species richness in this study, and derived the biodiversity impacts from the Sustainability Impact Metrics methodology, as follows. First, biodiversity loss was calculated as the difference in species richness between the norm for nature, based on a biodiversity factor for Switzerland (step 1), and the species richness in the area where wheat for bread was produced using different farming practices (step 2). The resulting biodiversity loss was converted into eco-costs per area (step 3) and was then related to the mass of bread to obtain the true cost of bread per kg (step 4). The monetization factor considered expresses the prevention costs to protect 1 m^2 applied to land with a biodiversity of 4000 vascular species per 10.000 km^2, which corresponds to a biodiversity factor of 1 (Sustainability Impact Metrics, 2024).

step-1 - biodiversity factor: is an indicator of species richness that is proportional to the number of species per area. It ranges from 1.25, as observed in Central America, which has over 5,000 species per 10,000 km2, to 0.025, as seen in Greenland, which has around 100 species per 10,000 km2. Barthlott's global diversity map (Barthlott et al., 2005) indicated that Switzerland has 2,000 to 3,000 species per 10,000 km^2. Consequently, we have assumed an average of 2,500 species per 10,000 km^2, corresponding to a biodiversity factor of 0.625.

step-2 - derivative factors by crop per practice: Species richness for wheat-growing areas was calculated by practice through a process of cross-referencing species richness data with georeferenced data on farming practices (Geodienste, 2024). The species richness was computed based on Agroscope's ALL-EMA Monitoring Programme (Agroscope, 2023). We obtain species richness results per 10m^2 which we project to 1km^2 using the R library "iNEXT", which extrapolates sampling-unit-based incidence frequencies with the assistance of rarefaction curves from 10 m^2 to 1 km^2. As a result, the average biodiversity richness for wheat production per practice, namely conventional, extensive, and organic farming, is 50.4, 58.5 and 83.1 species per 1 km^2, respectively. As a biodiversity factor of 1 is equivalent to 1000 species per 1 km^2 (Sustainability Impact Metrics, 2024), we divided the species richness by this value to convert our results to biodiversity factors.

step-3 - biodiversity loss and eco-costs: Biodiversity loss was calculated on the basis of the difference between biodiversity factors by practice and culture, and the norm for nature (i.e., Switzerland in our case study, see step-1). The monetary values were calculated by multiplying the losses by the corresponding eco-costs, i.e. a measure expressing the importance of the environmental load of a product in terms of the prevention of this burden (see Table 3).

step-4 - product burden allocation: The eco-costs, expressed per unit area, were converted into eco-cost per mass of crop according to the practice using Eq. (2).

$$TC_{i,k} = m_i \cdot EC_k / y_k \tag{2}$$

With:

Table 3
Eco-costs per practice transition (CHF/m^2).

Eco-costs	norm	conventional	extensive	organic
norm	0,000	3,537	3,487	3,336
conventional	−3,537	0,000	−0,050	−0,201
extensive	−3,487	0,050	0,000	−0,151
organic	−3,487	0,201	0,151	0,000

$TC_{i,k}$: true cost of wheat crops of bread i for practice k [CHF];
m_i : ratio of wheat for bread type i [kg wheat/kg bread];
y_k : yield of wheat crops for practice k [kg wheat/m^2];
EC_k : eco-cost per area unit for practice k [CHF/m^2];
k : type of pratice, namely conventional, extensive or conventional;
i : type of bread, namely whole or refined.

Based on this approach, eco-costs were estimated at 5.50, 6.57 and 8.20 CHF/kg for conventional, extensive and organic wheat respectively. Taking bread recipes into account, the eco-cost of biodiversity loss was estimated at 3.23, 3.86, 4.80 CHF/kg for wholegrain bread and 4.48, 5.35, 6.68 CHF/kg for refined grain bread.

2.3.3. Health costs of pesticides via ingestion

The toxicity of pesticides expressed in disability-adjusted life years per kg (DALYs/kg) enables us to calculate the loss of the equivalent of one year of full health, per kg of product consumed. The difficulty lies in measuring the pesticide content of the final product (i.e., bread in our case study), which is generally not available. We therefore used the Maximum Residue Limit (MRL) method (Sustainability Impact Metrics, 2023), which assumes that the food product contains the maximum amount of pesticides permitted by the regulations, following Eq. (3).

According to the Swiss ordinance (DFI, 2016), European regulations on MRLs prevail (European Commission, 2023), unless otherwise stated. We applied the MRLs for all the pesticides authorized for wheat in Switzerland according to the OSAV (OSAV, 2024), and derived the values per practice according to their requirement specification (DEFR, 1997). A default MRL of 0.01 mg/kg applies when a pesticide was not specifically mentioned (European Commission, 2023) for conventional farming. The use of inputs for organic farming is regulated by the DEFR ordinance (DEFR, 1997). No correspondence was found between the authorized substance and the active substance for wheat, which led us not to consider any pesticides for organic farming. Only herbicides are permitted in extensive farming, but we also took account of the specific requirements of *IPSuisse* label forbidding additional herbicides such as glyphosat IP-SUISSE (2025).

$$TC_{i,pesticides} = MF_{DALYs} \sum_p \text{health impact}_p \cdot MRL_p \tag{3}$$

With:

$TC_{i,pesticides}$: true cost of product i for pesticides [CHF/kg wheat];
health impact$_p$: health impact of pesticide p [DALYs/mg];
MRL_p : Maximum Residue Limit of pesticide p [mg/kg wheat];
MF_{DALYs} : monetization factor of DALYs [CHF/DALYs], see Table 2.

2.3.4. Health costs of dietary-risk-related diseases

The burden of dietary-risk-related diseases, expressed in DALYs, has made it possible to assess dietary-risk-related health costs. However, the main limitation lies in the independent study of individual components of the diet when they have an impact on each other. Therefore, The DALYs attributable to the food groups were assessed using the method and data of Schwingshackl et al. (2019), which estimates and ranks 12 food groups (including whole and refined grains) according to disability-adjusted life years (DALYs) from coronary heart disease (CHD), stroke, type 2 diabetes (T2D), and colorectal cancer (CRC) in 16 European countries. We selected the scenario D (single TMREL/significant food-disease associations) which was deemed most relevant as it provide a single optimum across all diseases.

Table 4
Pesticide authorized for wheat in Switzerland per type of farming practice, MRLs and associated health costs via ingestion.

Chemical name	Chemical class	DALY (Ingestion) [DALYs/kg]	Cost [CHF/mg]	MRL [mg/kg]	Conventional	Extensive	Organic
2,4-D	Herbicide, Plant Growth Regulator, Metabolite	0,12420	9.95E−03	2	✓	✓	×
Chlormequat	PGR	0,02619	2.11E−03	7	✓	×	×
Cypermethrin	Insecticide, Veterinary Treatment	0,06750	5.43E−03	0,01	✓	×	×
Dicamba	Herbicide	0,06750	5.43E−03	2	✓	✓	×
Ethephon	Plant growth regulator	0,16740	1.35E−02	1	✓	×	×
Fenoxaprop-p	Metabolite	2,45700	1.98E−01	0,01	✓	×	×
Fenpropidin	Fungicide	0,08640	6.93E−03	0,01	✓	×	×
Florasulam	Herbicide	0,01728	1.41E−03	0,01	✓	✓	×
Folpet	Fungicide	0,01242	2.21E−03	0,4	✓	×	×
Iodosulfuron-methyl-sodium	Herbicide	0,08910	7.13E−03	0,01	✓	✓	×
Mecoprop	Herbicide	0,22950	1.85E−02	0,01	✓	✓	×
Mepiquat Chloride	Plant growth regulator	0,00999	8.04E−04	3	✓	×	×
Metconazole	Fungicide	0,25380	2.04E−02	0,15	✓	×	×
Metribuzin	Herbicide	0,04860	3.92E−03	0,1	✓	✓	×
Metsulfuron-methyl	Herbicide, Metabolite	0,01377	1.11E−03	0,01	✓	×	×
Pendimethalin	Herbicide	0,00999	8.04E−04	0,05	✓	✓	×
Propoxycarbazone-sodium	Herbicide	0,00070	1.00E−04	0,02	✓	✓	×
Prothioconazole	Fungicide	0,02457	2.01E−03	0,1	✓	×	×
Pyroxsulam	Herbicide	0,00621	5.02E−04	0,01	✓	✓	×
Spinosad	Insecticide	0,19170	1.54E−02	2	✓	×	×
Spiroxamine	Fungicide	1,13400	9.11E−02	0,05	✓	×	×
Tebuconazole	Fungicide, Plant growth regulator	0,04050	3.22E−03	0,05	✓	×	×

step-1 - From DALYs per disease to total DALYs per food intake: From the Supplementary Information of Schwingshackl et al. (2019), for each country we extract the 2016 DALYs per country, the Population Attributable Fractions (PAF)(for each disease and food group) and the daily food group intake. We compute the DALYs per capita for each disease and country, by dividing the DALYs with the population, using data from the Population Reference Bureau (Population Reference Bureau, 2016). We then account for all diseases. Here, the PAF represents the proportion of disease burden that can be attributed to suboptimal consumption of food group i. The combined PAF is zero when consumption is optimal. We compute the DALYs attributable to food group i according to Eq. (4).

$$DALYs_i = \sum_{d} DALYs_d \cdot PAF_{d,i} \tag{4}$$

With:

$DALYs_i$: DALYs attributable to food group i [DALYs/person/yr];

$DALYs_d$: DALYs attributable to disease d [DALYs/person/yr];

$PAF_{d,i}$: PAF per disease d of food group i [%].

In our analysis, we performed curve fitting on the data using per capita intake and associated DALYs. To achieve a consistent trend with the highest coefficient of determination (R^2), we selected logarithmic and exponential models for whole grains and refined grains, respectively. Fig. 1 illustrates the relationship between per capita DALYs attributable to whole grains and refined cereals and their corresponding consumption levels.

According to the Global Dietary Database (The Global Nutrition and Policy Consortium, 2022), during the period 2015–2018, the average daily consumption of whole grains and refined cereals in Switzerland was 43.539 g and 73.103 g per person, respectively. These consumption levels were associated with 0.009162 and 0.000124 DALYs per person per year, respectively.

step-2 - From DALYs per food group to DALYs per product: We decided to account for dietary-risk-related health costs of bread as the health gained or loss through the consumption of an additional unit of whole and refined grains, considering the current diet. We used the following Eq. (5):

$$TC_{diet}(x) = r \cdot MF_{DALYs} \cdot f_i'(x) \frac{365.25}{1000} \tag{5}$$

With:

$TC_{diet}(x)$: health cost gained or loss through the consumption of an additional unit of bread [CHF/kg bread];

MF_{DALYs} : monetization factor of DALYs [CHF/DALYs], see Table 2;

$f_i(x)$: DALYs per capita as a function of the intake, see Fig. 1;

$f_i'(x)$: derivative of DALYs as a function of the intake [DALYs/capita/g/d];

x : intake [g/d];

$f_{WG}(x) = 0.0128 - 0.00222 * ln(x)$[DALYs/capita/g/d]: DALYs per capita as a function of whole grains intake, see Fig. 1;

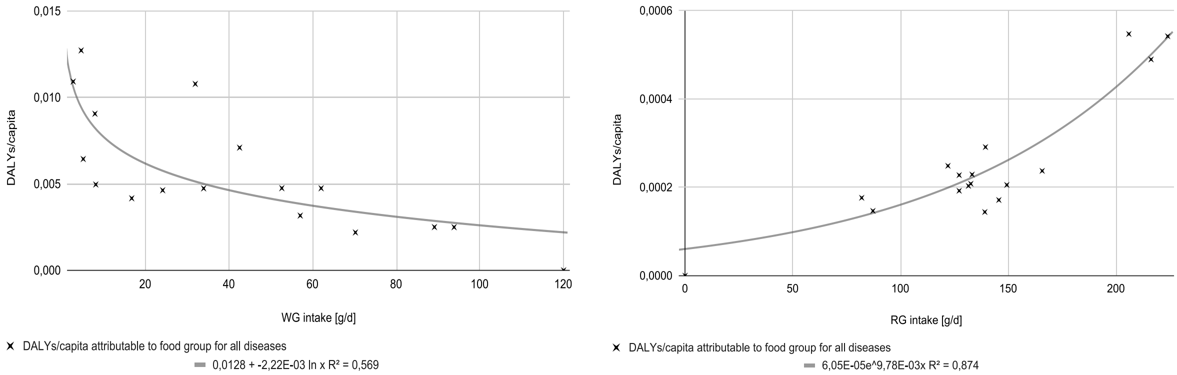
$f_{RG}(x) = 0.0000605 * e^{0.00978x}$[DALYs/capita/g/d]: DALYs per capita as a function of refined grains intake, see Fig. 1;

$r = 0.5865$[kg i/kg bread] : ratio of i in bread;

$\frac{365.25}{1000}$: unit conversion factor [d/y/g/kg].

2.3.5. Overworked hours method

To estimate the monetary value of excessive working hours in agriculture, we use the general legal threshold of 50 working hours per week as defined in OLT 1, art. 9, al. 3, LTr (Assemblée fédérale de la Confédération suisse, 1964), instead of the exemption currently applied to the agricultural sector (OLT 1, art. 2, al. 1, let. d, LTr (Assemblée fédérale de la Confédération suisse, 1964)). The underlying assumption is that farmers should have the financial autonomy to either perform these additional hours themselves or hire someone to delegate. The calculation is based on two key inputs: (1) Agridea's technical estimates of the annual labor requirements to manage one hectare of wheat (Agridea, 2022), and (2) national statistics indicating that farmers work an average of 66 h per week (OFS, 2024b). By comparing the actual weekly workload of 66 h with the legal limit of 50 h, we derive the proportion of labor time that exceeds the legal threshold, representing "overtime". This proportion is then applied to the annual labor requirement per hectare of wheat to estimate the number of overtime hours associated with wheat production. These hours are subsequently monetized using the average hourly wage of a medium-skilled farm worker (USP et al., 2023).



(a) Wholegrains **(b)** Refined grains

Fig. 1. DALYs per capita as a function of food group intake.

Table 5
Product allocation for the production system contribution.

Product allocation	Unit	Conventional	Extensive	Organic
Contributions to the production system	CHF/ha	128.31	528.31	1328.31
Wheat yields per practice	kg/ha	6425	5305	4069
Allocation for wholegrain bread	CHF/kg	0.012	0.058	0.191
Allocation for refined grain bread	CHF/kg	0.016	0.081	0.266

2.3.6. Public spendings

The subsidies were derived from the Swiss government's contributions to agricultural producers (see Table 5). These include direct payments, production and sales promotion, improvement of the production base and social measures. We will explain our methodology through the example of the contribution to the production system, which turned out to be the most substantial subsidy in our case study.

Step- 1 - contributions and dependencies: Each contribution (i.e. subsidy) depends on specific allocation criteria (OFAG, 2024), such as cultivated area, farm size, farming practices, crop and livestock production, slope and altitude of the field, etc. Around 130 contributions were examined to determine their eligibility in the context of wheat cultivation by organic, extensive and conventional farming (see Supplementary Information), also taking account of incompatibilities. For example, the production systems contribution comprises 22 sub-contributions, only 9 of which were eligible for organic farming, 7 for extensive farming, and 6 for conventional farming.

Step 2 - derived contribution: the total amount of contributions is indicated in the annual report on agriculture. Areas cultivated using organic, extensive and conventional practices are declared directly. However, more specific contributions such as that for appropriate soil cover must be derived. Around half of the cultivated land benefited from this subsidy (200CHF/ha). In the absence of detailed data, we have considered a distribution of the total amount in proportion to the area cultivated per crop and per practice (OFS, 2024a), which leads to an amount of 38.5 CHF/ha on average for wheat. Overall, the contributions are estimated at 128, 528 and 1328 CHF/ha for conventional, extensive and organic farming.

Step 3 - product allocation: the subsidies per hectare and per practice were allocated to bread on the basis of the wheat yields per practice and the mass of flour required for each bread recipe, following Eq. (6). The yields per practice are based on the Ecoinvent database, and we considered the typical Swiss bread recipe for the mass allocation. For the contribution to the production system, this leads to an estimate of 0.01, 0.06 and 0.19 CHF/kg for wholegrain bread produced by conventional, extensive and organic farming, respectively, and 0.02, 0.08 and 0.27 CHF/kg for refined bread. Subsidies are mechanically higher for refined flour, because it requires more wheat than wholegrain flour.

$$TC_{i,j}^{k} = S_{i,j}^{k} / y_{i,j} \cdot r_i \tag{6}$$

With:

$TC_{i,j}^{\ k}$: true cost of product i for practice j for criterion k in CHF/kg;
$S_{i,j}$: subsidies for product i for practice j in CHF/ha;
$y_{i,j}$: crop yield for crop i for practice j for criterion k in kg/ha;
r_i : crop requirement (recipe) for crop i in kg/kg.

2.4. Food wastes

In Switzerland, more than half of all the bread produced goes uneaten, making it the most wasted food in the country (Beretta and Hellweg, 2019). Our method includes the costs associated with production (all categories but health) as well as the consumption stages (health impacts). We have therefore considered both the production-based analysis and the consumption-based analysis. We compute the production- and consumption-based costs using the following Eqs. (7) and (8):

$$\text{Production-based costs} = TC_{prod} + TC_{cons} \cdot (1 - \text{Waste [\%]}) \tag{7}$$

$$\text{Consumption-based costs} = \frac{TC_{prod}}{1 - \text{Waste [\%]}} + TC_{cons} \tag{8}$$

With:

TC_{prod}: costs occurring during production [CHF];
TC_{cons}: costs occurring during consumption [CHF].

The cost based on production refers to the production of 1 kg of bread, which means that the impacts on consumption only take into account the bread actually consumed (i.e. 0.45 kg). The costs based on consumption refer to the consumption of 1 kg of bread, which means that the impacts on production take into account the bread actually produced given the wastes to reach 1 kg of consumption, i.e. 2.22 kg.

3. Results

Fig. 2 shows the true cost of bread from consumption- and production-based perspectives. The overall results highlight three key

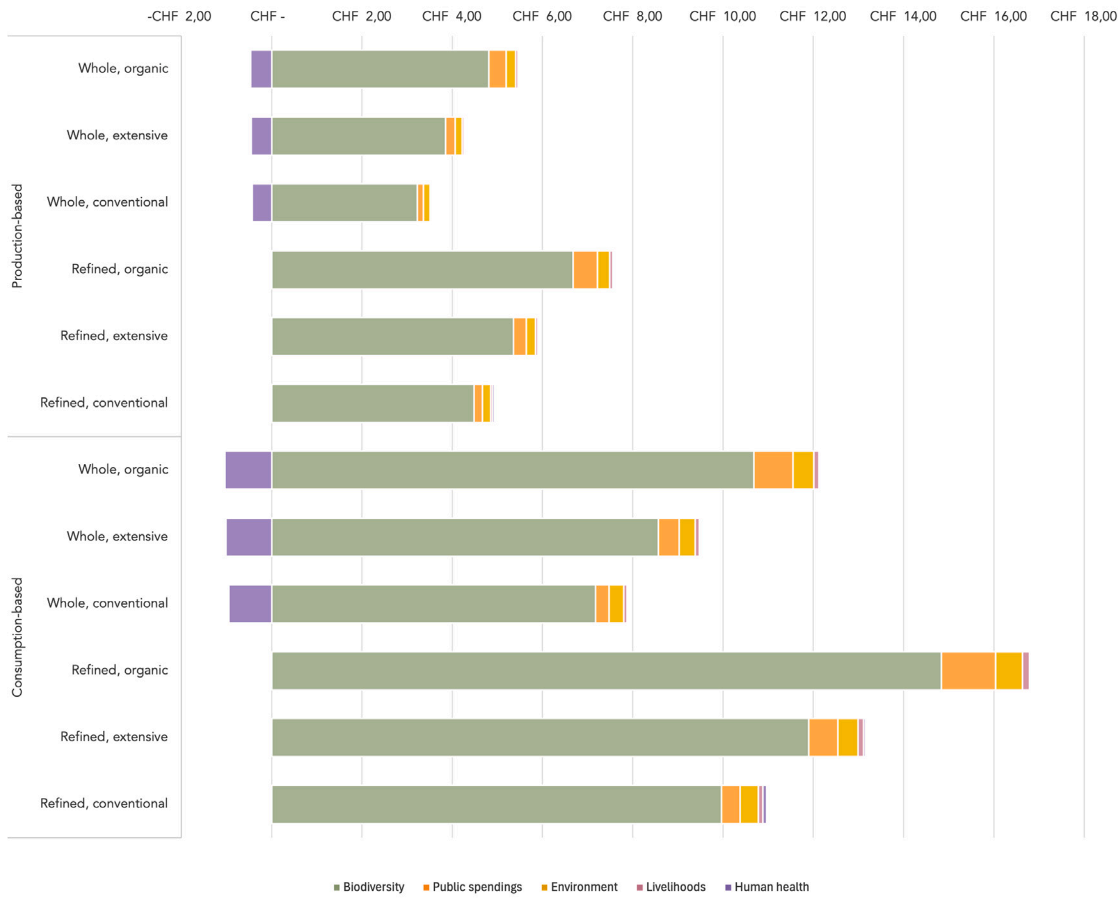


Fig. 2. True cost per kg of whole and refined bread from conventional, extensive and organic agriculture. Results are displayed for production and consumption-based costs and are aggregated per overall impact category: biodiversity, public spendings, environment, livelihoods and human health.

points. Firstly, the effects on human health distinguish breads made from refined grains from those made from wholegrain. Given the low consumption of wholemeal cereals in the Swiss diet, increasing consumption of wholemeal bread would reduce the number of DALYs. It is therefore beneficial, which translates into a negative cost (see Section 3.1). Secondly, the impacts on biodiversity distinguish between agricultural practices ranging from organic to conventional farming. Despite the better performance of organic farming per area, conventional practices outperform extensive and organic practices when expressed per mass produced, despite their greater use of inputs. This is due to the yield gaps. Third, consumer waste levels are so high that the difference between the true cost from a consumption point of view is up to 80% higher than from a production point of view. Consequently, production-based costs range from 3.11–4.99 and 4.94–7.57 CHF for whole and refined bread respectively, and consumption-based costs range from 6.92–11.09 and 10.97–16.82 CHF. Expressed per daily bread portion consumed per person in Switzerland (115 g (Confédération Suisse and OSAV, 2017)), production-based results are ranging from 0.80–1.28 CHF for whole bread, and 1.26–1.93 CHF for refined bread. For both types of bread, impacts on biodiversity account for the highest proportion of costs, at around 81% for production-based costs and 90% for consumption-based costs.

3.1. Biodiversity

Overall, biodiversity-related costs range from 7.17 to 14.84 CHF/kg for conventional wholegrain and organic refined bread, from a consumption perspective. These costs would be more than halved per kg of bread produced if the bread was not wasted so much (55%). According to the land use eco-cost methodology, biodiversity-related costs depend on land use intensity and the impact of agriculture on biodiversity richness. Organic farming has the lowest impact on biodiversity richness per area, followed by extensive and conventional practices. However, this gain is outweighed by differences in yield, so that the least land-intensive bread has the least impact on biodiversity, and the most extensive bread has the least per kg of product. As shown in Fig. 3, organic agriculture has higher biodiversity and environmental costs per unit produced, but lower costs per unit area. On average, considering our biodiversity methodology, organic is 6.0% less impactful when expressed per cultivated area, and 32.9% more impactful when expressed per mass produced. So, the context of land use in terms of demand and conversion is essential to interpret these results beyond the product level.

Our study shows that biodiversity accounts for the majority of the true cost, similar to another study on oil (Bellon et al., 2024). Our results show a contribution to costs of at least 80% whereas theirs is around 50%, which can be explained by considering the different methodologies, products and geographical scope.

3.2. Human health

The health costs of refined bread are high in relation to dietary-risk-related diseases, due to the typical Swiss diet, which is too low in fiber (ie an indigestible plant nutrient with a positive effect on digestion). Unlike wholegrain flour, white flour contains almost no dietary fiber, resulting in an estimated dietary-risk-related cost per kg of bread consumed of CHF 0.025, and up to CHF 0.08 for pesticide ingestion, depending on practice. Pesticide costs in conventional farming (0.08 CHF/kg) are divided between fungicides (59%), herbicides (7%) and other products such as insecticides and growth regulators. Extensive

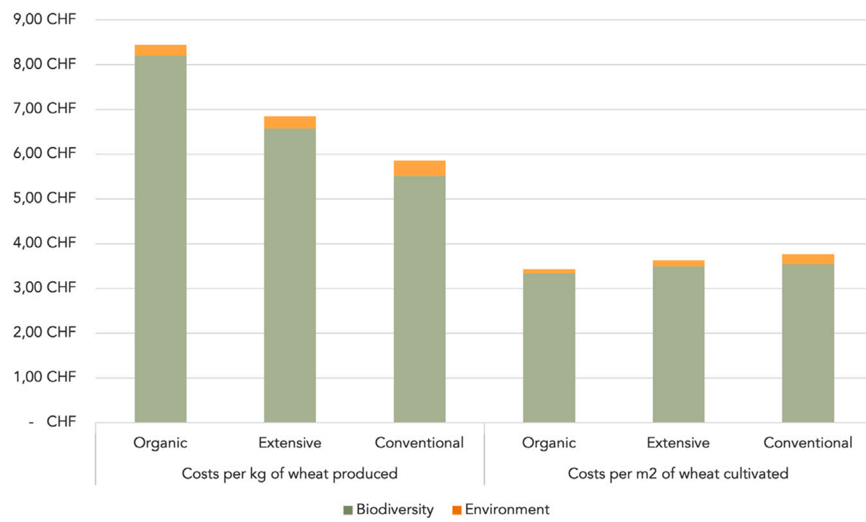


Fig. 3. Comparison of biodiversity and environment costs when expressed per kg of wheat produced versus m^2 of wheat cultivated.

farming regulations prohibit several pesticides, making herbicides the main driver of pesticide costs (99%), dividing costs by four compared to conventional farming (i.e., 0.02 CHF/kg). For wholegrain bread, health costs are linked solely to pesticides, with 0.06, 0.02 and 0 CHF/kg for conventional, extensive and organic farming respectively. Given the suboptimal fiber intake of the Swiss population, the health impact associated with wholegrain bread is an estimated benefit of $-1.86 \cdot 10^{-5}$ DALYs/kg consumed, or −1.04 CHF/kg consumed.

Our methodology considers the health gain or loss due to the consumption of an additional kg of bread (per year) with respect to the current production. The further one strays from optimal consumption, the higher the costs or benefits. Therefore, the full extent of health costs due to underconsumption of whole grains is not embodied. In Switzerland, the current underconsumption of wholegrains (43.5 g/d per person (The Global Nutrition and Policy Consortium, 2022)) is responsible for 0,004422 DALYs/person/y i.e., 419 CHF/person/y.

3.3. Environment

Fig. 4 shows the true cost by environmental sub-category. A slightly weaker impact is observed when choosing wholegrain bread over refined bread, regardless of the farming practice, due to the different amounts of wheat necessary. As with biodiversity, environmental costs often favor the least land-intensive breads. Costs range from CHF 0.26 to CHF 0.50 for whole grain and organic refined bread, respectively. Global warming is the main environmental cost (34% to 52%), with bread type being the most discriminating factor due to processing yields. Refined breads are the worst for global warming, regardless of farming practices. Marine eutrophication is the second most important cost (19%–27%), with land use intensity being the main factor, which favors conventional and extensive farming over organic farming. A similar pattern can be observed for terrestrial acidification. Finally, the impacts of freshwater, terrestrial and marine ecotoxicity are weaker and narrower. Wheat and yeast production are the most important stages, followed by bread-making (milling and baking).

3.4. Livelihoods

The cost of overworked hours varies between CHF 0.03 and 0.07 per kg. In our case study, overworked hours depend on wheat yields and flour requirements for each type of bread. Conventional wholegrain bread, which offers the highest yields, limits the impact of overtime (CHF 0.03/kg). Conversely, organic refined bread has the lowest cost, at CHF 0.07/kg. This metric does not differentiate between various production systems salary and labor intensity. Therefore, as the extensive and organic yields are lower than in conventional farming, the associated livelihoods costs are higher.

3.5. Public spendings

Fig. 5 shows subsidies (i.e., contributions in Switzerland) to agricultural producers, administrated as direct payment and expressed in CHF/kg per type of bread and per practice. The results indicate that "contributions to production systems", i.e., support for production that is particularly respectful of resources, are among the most significant subsidies but also the most discriminatory, with approximately CHF 1,200 and CHF 400 per hectare for organic and extensive farming (or CHF 0.06 to 0.27/kg). The contribution to security of supply is the second largest subsidy, but it is sensitive to yields from field to fork, and therefore to the type of cereal and farming practices (from CHF 0.08 to 0.17/kg). Contributions to biodiversity are estimated at around CHF 0.02/kg, which is far below the estimated environmental cost of biodiversity (between CHF 0.8 and 2.33/kg). Overall, these subsidies range from CHF 0.13 to CHF 0.54, depending on the type of cereal and the farming practices used. More importantly, the figure illustrates the disparity between subsidies and the true cost of bread (the higher the 0–100 score, the lower the true cost). Conventionally produced wholegrain bread has one of the lowest true costs, but it is the least subsidized. Conversely, organic bread made from refined cereals is the most subsidized although it suffers from the highest costs. Overall, the subsidies seem disconnected from the true cost.

4. Discussion

4.1. Methodology and limits

There are several limitations to consider in the methodology, including the combination of multiple methodologies, data availability and compatibility, and the choice of baselines for indicators such as health and biodiversity. Our approach combines multiple methods to cover the widest range of sustainability metrics. However, it is sometimes limited by data availability and compatibility because the impacts must be assessable and monetizable simultaneously. Additionally, aligning data and methods raises ontological questions to ensure a match between the impacts, items, and scope of the different methods, which limits the options for combining methods and thus the scope of the sustainability impacts we aim to cover. For example, unpaid family work, salt-related health impacts, and production system resilience should be considered, but we could not access the necessary data.

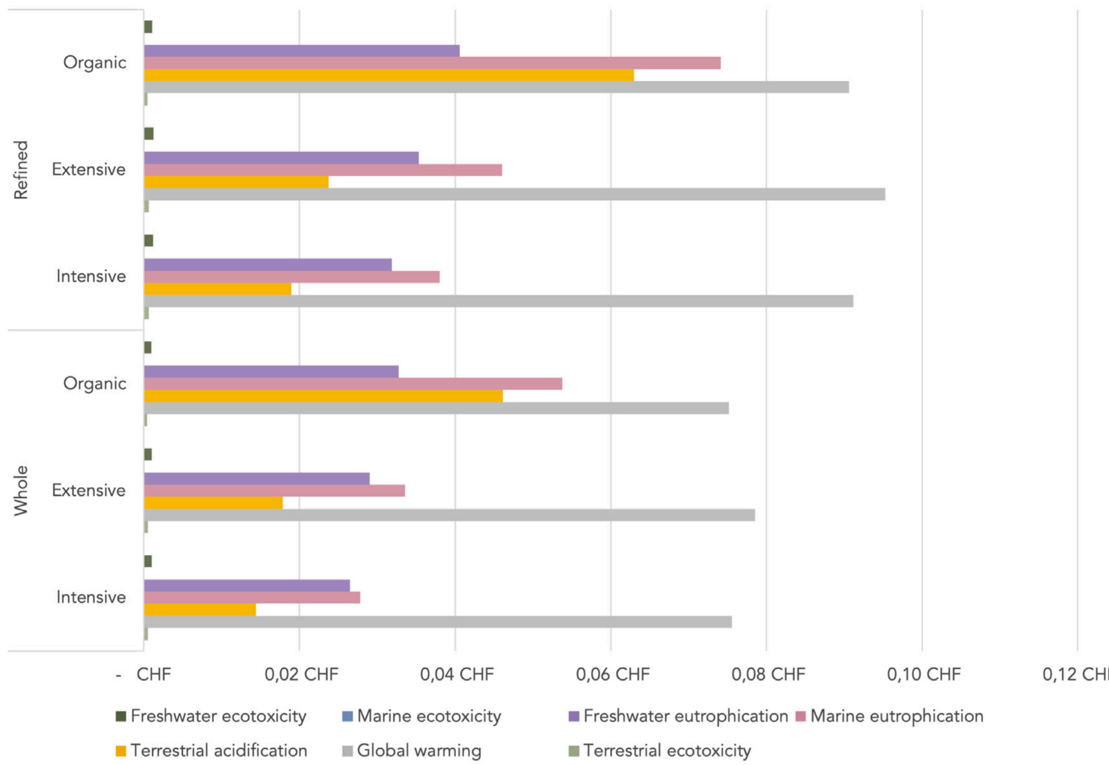


Fig. 4. True cost of environmental impacts valued using LCA per kg of whole and refined bread from conventional, extensive and organic agriculture.

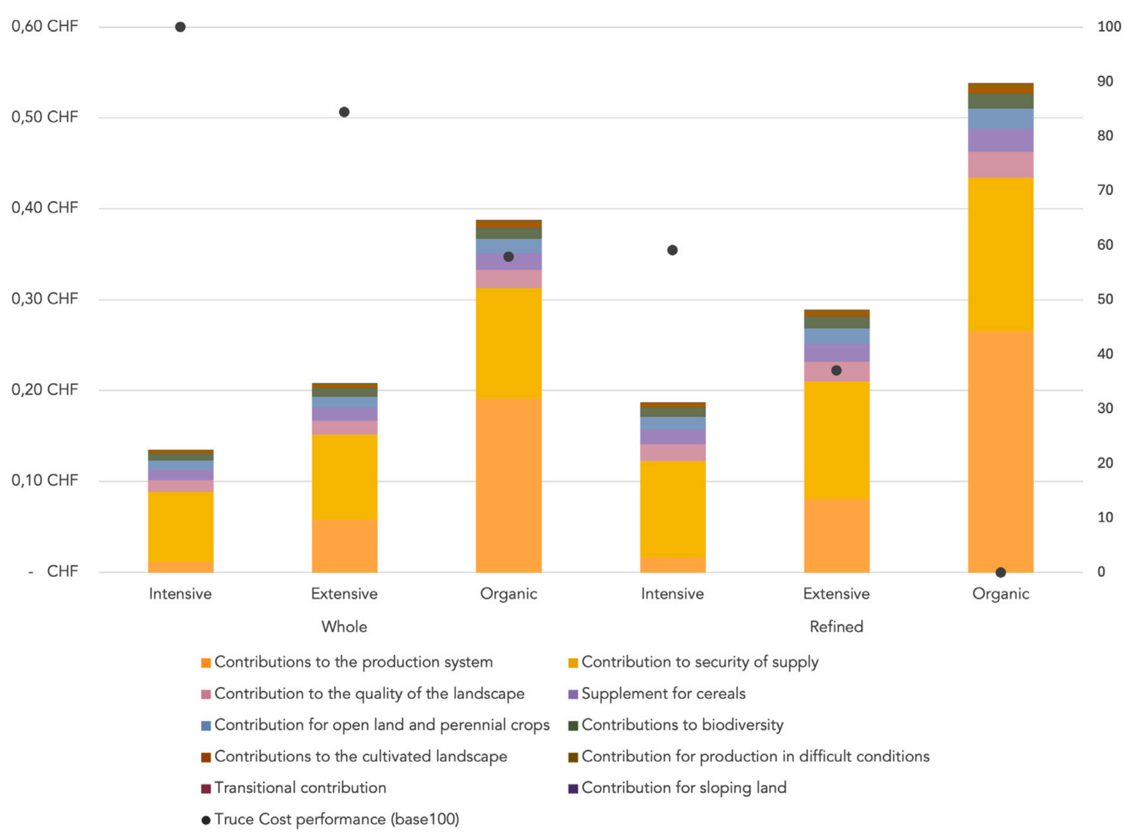


Fig. 5. Subsidies per contribution to agricultural producers per kg of whole and refined bread from conventional, extensive and organic agriculture, and true cost performance in base 100. This allows to visualize the subsidies received against the ranked true cost performance.

As with other true cost studies (Michalke et al., 2023; Bellon et al., 2024; FAO, 2024), we also did not sufficiently consider the potential benefits and mostly focused on costs, except for dietary-risk-related impacts. This underscores the importance of the baselines in the methodology. Some baselines can be defined straightforwardly, such as setting a threshold or banning undesirable practices. Other baselines can be more complex, such as those for biodiversity. The costs of land use can be determined by using the natural state or changes in practices (e.g., from conventional to organic) as a reference point (Sustainability Impact Metrics, 2024). In the first case, practices are evaluated based on the loss of biodiversity richness compared to the natural state. This implies costs for all practices. Another option is to take into account the benefits of adopting a farming practice that is more respectful of biodiversity. In such cases, conventionally farmed land is considered the reference rather than land in its natural state. This implies no biodiversity costs for land that is conventional farming and negative costs (benefits) for more extensive practices. However, applying this approach at the product level would not take into account the potential increase in demand for land due to the lower yield of more extensive practices. This is why we have chosen the first approach.

4.2. Results and implications

By essence, the TCAF approach enables us to express all impacts in monetary terms, questioning burden sharing among the impact categories (e.g., predominance of biodiversity and health impacts in our case, but also at the global scale), and in the value chain (e.g., consumers for health, producers for environment and livelihoods). A value chain must be considered as a whole, and the breakdown of impacts by stage does not necessarily reflect responsibility or burden sharing. Similarly, the predominance of biodiversity impacts in monetary terms over other impacts should not necessarily be prioritized over environmental, health or livelihood issues, as these impacts are not substitutable. TCAF must be used as a global tool to rethink the system as a whole and minimize the overall true costs. For example, it can encourage consumers, support policy development and reallocate subsidies more effectively.

As previously discussed, some impacts can result in both negative and positive costs, such as the dietary-risk-related impact. Although this duality may not be immediately intuitive, it reflects here the bidirectional nature of health impacts associated with dietary patterns. Consuming certain food groups, such as salt, sugar, saturated fats, and refined cereals, has been linked to negative health outcomes, which generate costs for individuals and society. On the other hand, increased consumption of certain food groups, such as vegetables, fruits, and in this case, whole grains, contributes to improved health outcomes, which can be considered as societal benefits. Our results show negative costs due to underconsumption of whole grains in Switzerland, in line with the latest SOFA report from the FAO showcasing the lack of whole grains as the main contributor of dietary-risk-related costs in Switzerland and globally (FAO, 2024). These negative costs therefore express benefits created by the consumption of a given food considering the current diet. In this study, we focus on assessing costs rather than translating them into prices. While these benefits and costs are presented on the same graphical scale as other impacts in the analysis, this should not be interpreted as an attempt to aggregate all values into a single “true cost”, or even “true price”. Rather, they should be seen as an important indication of the costs/benefits that can be avoided/generated when incentives are in the right place at all stages of the value chain.

Product level analysis is also to be considered carefully, as expressed per mass. Our results show that conventional production performs better than the other practices, which differs when expressed per area, in line with previous studies (Tuomisto et al., 2012; Crosnier et al., 2025). In particular, a TCAF case study assessing the environmental and biodiversity costs per hectare of an organic and a conventional farm in Germany shows higher benefits for the organic farm (Gemmill-Herren et al., 2021). However, our results are opposite to a study comparing the true cost of organic and conventional products based on LCA, underlining the advantages of organic practices in most cases (Michalke et al., 2023). Our results differ because they adjusted the LCA processes to account for different scenarios, whereas we did not adjust them because they already corresponded to wheat production in Switzerland under conventional, extensive, and organic agriculture. However, the use of LCA for impact assessment has been criticized when comparing conventional and organic agriculture (van der Werf et al., 2020). Critics include the lack of biodiversity and soil impacts, as well as the implicit favoring of conventional agriculture and land sparing due to the functional unit of mass of food produced. Therefore, results must be carefully considered given these limitations. Focusing on the farm level and its specificities could provide a better overall picture of farm output sustainability, regardless of the overall production method, as there is significant environmental impact variability when comparing organic and conventional agriculture (Sanders et al., 2025). Nevertheless, such approach requires primary data and significant investments. In the context of this case study, our main objective was to expand the TCAF methodology and therefore provide a concrete assessment of a product. We emphasize the need for future studies to consider a systemic approach.

Despite the lack of a standardized and widely accepted methodology framework, we have reached a turning point in the TCAF approach. The FAO has published the first true cost estimates at the global and national levels in the 2023 and 2024 editions of the State of Food and Agriculture reports (FAO, 2023, 2024). The next critical step is to consider the policy implications and explore strategies to incentivize the food and agriculture towards a more healthy and sustainable system. Ongoing projects at both Swiss, European and international levels (TRUE-COST-CH, 2024; PLAN’EAT, 2022) aim to address the methodological gaps and explore implementation pathways.

5. Conclusion

This paper proposes a TCAF methodology applied to wholemeal and refined bread produced by conventional, extensive and organic farming in Switzerland. The study incorporates widely accepted indicators, such as costs derived from life cycle assessment (LCA) impacts. These are complemented by other indicators developed or derived to broaden the scope of sustainability impacts, such as biodiversity and food-related diseases. These latter indicators are generally absent from product level TCAF studies, but the results reveal that they contribute significantly to overall costs, showing higher costs than the limited existing literature, which focuses mainly on environmental impacts. However, further research is needed to overcome the limitations of the product level approach, such as taking account of wider systemic impacts (e.g., resilience, land availability). Our case study aims to pave the way for concrete applications of TCAF at the product level and to engage stakeholders in discussions about its implications and methodology.

CRediT authorship contribution statement

Agathe Crosnier: Writing – original draft, Methodology, Formal analysis. **Gino Baudry:** Writing – original draft, Methodology, Formal analysis. **Laurence Jeangros:** Writing – original draft, Methodology, Formal analysis. **Eliane S. Meier:** Writing – review & editing, Resources, Methodology. **Giulio Cisco:** Writing – review & editing, Methodology. **Laura Spring:** Writing – review & editing. **Dominique Barjolle:** Writing – review & editing.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used DeepL Write in order to improve language and clarity. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Declaration of competing interest

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

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Data availability

The complete data is open access: https://github.com/acrosnier/True-Cost-Accounting-for-Food-application-environmental-social-and-health-impacts-of-bread---Data.

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