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Comparison of exemplary crop protection strategies in Swiss apple production: Multi-criteria assessment of pesticide use, ecotoxicological risks, environmental and economic impacts

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ABSTRACT

Plant protection products (PPP) are used to protect apples from pests and diseases and to maintain high yields and fruit quality. Alternatively, non-chemical plant protection measures can be applied to reduce the use and ecotoxicological risks of PPP. However, additional materials, energy or labor are needed, which can have an impact on the environmental or economic performance.

To investigate possible trade-offs, this multi-criteria analysis examined different apple production systems based on exemplary crop protection strategies in Switzerland. One integrated crop protection strategy complying with the Swiss Proof of Ecological Performance (PEP2018) was used as a reference, and three exemplary strategies were compared to this reference. The integrated «PPP Reduced» strategy assumed a minimal use of synthetic PPPs in combination with a range of alternative plant protection measures to avoid yield losses. The conventional «High yield» strategy assumed maximum yields with minimal restrictions on the use of synthetic PPPs and fertilizer. Finally, the «Organic» strategy represented typical organic apple production without the use of synthetic PPPs.

To compare the performance of these strategies, 13 indicators were calculated, covering four aspects. PPP use was analyzed with the treatment frequency index, local ecotoxicological risks for next-to-field habitats were modeled with SYNOPS, global environmental impacts of 1 kg apple were analyzed with life cycle assessment (LCA) and economic impact on farms was assessed with a full-cost calculation.

Compared to the «PEP2018» strategy, the «PPP Reduced» strategy performed much better in terms of ecotoxicological risks and biodiversity, but was not profitable due to high investments resulting in a negative farmer's hourly wage. The ecotoxicological risks were comparable between the «PEP2018» and «High yield» strategies, with the latter performing much worse in terms of biodiversity and global warming potential. Despite the high capital and labor input, the «High yield» strategy was much better in terms of resource use and farmer's hourly wage. The «Organic» strategy had the largest impact (per kg of apples) on most global environmental indicators, but performed much better on ecotoxicological risks and also on farmer's hourly wage.

The results of this study show that reducing the use of PPP and the associated risks in apple orchard without environmental or economic compromises is challenging. None of the strategies examined performed better than the other strategies in all indicators assessed. However, this approach could contribute to identify and design more sustainable crop protection systems in apple production.

1. Introduction

In our food systems today, plant protection products (PPPs) play an important role in food security by reducing yield losses caused by pests and diseases (Savary et al., 2019). However, PPPs can have negative effects on biodiversity (Hallmann et al., 2014; Stehle and Schulz, 2015)

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Nomenclature

AEI	agri-environmental indicators
GWP	global warming potential
«High yield»	crop protection strategy with maximum yields
I_{ref}	the indicator value of the reference strategy *ref* («PEP2018»)
I_S	the indicator value of the strategy *s* (either «PPP Reduced», «High yield», or «Organic»)
IPM	integrated pest management
LCA	life cycle assessment
«Organic»	crop protection strategy for average organic production
PEP	proof of ecological performance: a Swiss standard for good environmental practices; compliance with this standard is a prerequisite for receiving direct payments
«PEP2018»	crop protection strategy representing average production according to the guidelines of the Swiss Proof of Ecological Performance of 2018
PPP	plant protection products
«PPP Reduced»	crop protection strategy with a minimal use of synthetic plant protection products
SALCA	Swiss Agricultural Life Cycle Assessment
SYNOPS	a model to assess the environmental risk potential of pesticides
TFI	treatment frequency index

and human health (Alavanja and Bonner, 2012). National policies in Europe are therefore increasingly aimed at reducing PPP use and associated risks.

Apples, one of the most consumed fruits in the European Union and Switzerland (FAO, 2021), are among the crops in Switzerland with the highest PPP treatment frequency and the highest PPP amounts applied per hectare (de Baan et al., 2015), also in organic systems. Reducing the use of PPPs in permanent crops such as apples is a challenge because crops cannot be rotated annually, which encourages an increase in infestation or infection levels from one year to the next (Simon et al., 2010). In addition, the fruit quality of apples must be high in order to be able to store the fruit for several months and to meet the high demands of trade and consumers. Alternatives to chemical pest control have been developed, such as biological control (e.g. natural enemies, mating disruption by pheromones) or physical measures (e.g. mechanical weed control or rain cover to reduce fungal infections) to protect crops from pests and diseases while reducing the use of PPPs. However, some of these alternatives require additional resources, such as insect nets, rain cover or machinery for mechanical weed control as well as increased labor or financial capital (Ackermann et al., 2021). In addition, alternative crop protection measures are not always as effective as chemical measures, resulting in lower yields, which in turn can lead to higher environmental impacts per product unit (e.g. higher land use per kg apple) (Tuomisto et al., 2012). While different crop protection strategies may cause different environmental (Alaphilippe et al., 2013; Goossens et al., 2017) or economic side-effects (Caffi et al., 2017), they also differ in their effectiveness in reducing PPP use (Simon et al., 2011) and ecotoxicological risks (Mouron et al., 2012). In addition, the different apple production systems, such as conventional, integrated or organic production, have specific restrictions or requirements regarding other inputs, such as fertilizers, and different conditions prevail on the market. As these interrelationships can be complex, a thorough evaluation of different crop protection strategies in different apple production systems is required with regard to the trade-off between PPP use, ecotoxicological risks, environmental and economic impact.

To compare the environmental impacts of apple production systems, some previous studies have conducted a life cycle assessment (LCA) of conventional, integrated, and organic orchards. The LCA method quantifies the potential environmental impact of a product (e.g. 1 kg apples) over its entire life cycle, from the extraction of raw materials, through production and distribution of the product, to waste disposal (ISO, 2006). LCA strives for a comprehensive assessment of all relevant environmental impacts, such as climate change, use of resources (material or energy), biodiversity, eutrophication, acidification, etc. Alaphilippe et al. (2013) compared different apple production systems and within each system three different apple cultivars. Their results show that the low-input system combined with a cultivar with low disease susceptibility had the best environmental performance while organic systems showed often higher environmental impacts per product unit. Goossens et al. (2017) compared the environmental impact of three production systems over the entire lifespan of orchards, including lower production phases of young and old trees and showed that the integrated system had the lowest environmental impact. Longo et al. (2017) showed that organic apples had slightly lower impacts during apple cultivation but overall environmental impacts of both systems were similar because they were dominated by post-harvest processes and transport.

However, none of these studies specifically considered the environmental impact of alternative crop protection measures (such as rain covers or insect nets).

Other studies analyzed the economic and environmental impacts of plant protection strategies in apple orchards. Caffi et al. (2017) investigated the advantages and disadvantages of using innovative integrated pest management (IPM) systems for different pests and diseases in pome fruit production in Europe and analyzed the overall sustainability including ecotoxicological risks and economic impacts. Mouron et al. (2012) investigated the sustainability of four innovative crop protection strategies in apple orchards of five European regions. However, both studies focused on IPM and excluded organic or conventional systems. In addition, they have used a multi-criteria assessment method, which involved subjective weighing of the evaluation criteria. For example, in the method proposed by Mouron et al. (2012), the local ecotoxicological risks of crop protection strategies accounted for only 2% of the total calculated sustainability score . Such an aggregated assessment cannot identify the existing trade-offs.

The aim of our study was to investigate and compare the performance of simulated exemplary crop protection strategies in Switzerland for conventional, integrated and organic apple production systems, assessing PPP use, local ecotoxicological risks, global environmental impacts and economic effects. Although Switzerland does not export any significant quantities of apples, the Swiss apple production is very important for domestic consumption and provides about 90% of the quantities of apples consumed in Switzerland (BLW, 2021a). Three apple crop protection strategies were compared to a reference strategy on the basis of 13 indicators. The assessment of 13 quantitative indicators allows to transparently identify potential synergies or conflicts between PPP use and ecotoxicological risks, global environmental impacts and economic impacts of crop protection strategies. The assessment was carried out using different perspectives. For ecotoxicological risks, a local perspective was used to identify risks for organisms living in the surrounding terrestrial and aquatic ecosystems. The environmental impacts of the crop protection systems were investigated within a LCA framework, taking a global perspective as the impacts are distributed over the entire life cycle of the products and can occur in different world regions. For the economic impact, the farmer's perspective is relevant, as only profitable crop protection strategies will be implemented. In order to provide decision support for the further optimization of apple crop protection strategies, the most important factors for each indicator were identified. Finally, a multi-criteria assessment was carried out to make the results of the 13 indicators more accessible. Each strategy was

Table 1
Summary of the most important differences between the four evaluated crop protection strategies for an average full yield year. For differences in the development phase, see SI.

	«PEP2018»	«PPP Reduced»	«High Yield»	«Organic»
General parameters				
Short description	Average production in 2018; mainly synthetic PPP	Reduced PPP use and low residues, without yield losses	Maximized yield	Average organic production in 2018
Apple variety	Gala	Bonita	Gala	Gala
Nets/covers	Hail net	Hail net; insect net; rain cover	Hail net	Hail net
Irrigation	–	Drip	Drip and over-head	–
Fertilization	Mineral	Mineral	Mineral	Organic
N/ha (kg/ha)	63	63	126	20
No. of PPP treatments (no. of active ingredients)				
Fungi-/ bactericide	16 (10)	7 (6)	16 (10)	16 (5)
Insecticide	5 (5)	3 (3)	8 (8)	3 (3)
Herbicide	4 (5)	0	5 (6)	0
Plant growth regulator	1 (2)	1 (2)	1 (2)	–
Living organisms and viruses	–	5 (2)	–	5 (3)
Pheromone dispenser	–	Yes	–	Yes
Hot water treatment	–	–	–	Yes
Direct payments, yields, prices				
Direct payments (CHF/ha/yr)	1300	2100	–	2900
Yield (t/ha)	38.0	38.0	60.0	24.7
Storage loss (%)	10	10	10	20
Share 1st class apples (%)	75	75	90	75
Price 1st class apples (CHF/kg)	1.05	1.05	1.05	2.20
Price 2nd class apples (CHF/kg)	0.45	0.45	0.45	0.33

compared to the reference strategy, and differences in the results of the indicators were classified as much better, better, similar, worse or much worse performance than the reference.

2. Methods

2.1. Description of the four exemplary crop protection strategies

To compare the effects of different crop protection strategies, four exemplary crop protection strategies were created, which could be applied in this way in Swiss apple orchards, but differed in essential points. As a reference, a crop protection strategy in integrated production was chosen in which synthetic PPPs were used in accordance with the guidelines of the Swiss Proof of Ecological Performance of 2018 («PEP2018»). The strategy «PPP Reduced», which is also based on the principles of an integrated production system, aimed at minimising the use of synthetic PPPs and possible residues on the apples without causing yield losses. The strategy «High Yield» was based on a conventional production system and focused on maximizing yields while reducing production risks. The strategy «Organic» reflected a typical organic apple production in Switzerland in 2018.

The exemplary crop protection strategies represent a typical crop protection strategy for each production system (integrated, conventional, organic), in an average year in relation to damage and pest pressure, weather conditions and market situation and in an average farm.

2.1.1. Cultivation parameters

General cultivation parameters were defined for all strategies based on existing literature and expert advice (see Supporting information (SI) Table S2). For all strategies, a 15-year lifespan (three-year development, twelve-year full yield phase) was assumed for the apple orchard covered with a hail net. After harvesting, a 6-month storage in controlled atmosphere was considered. To ensure comparability, the assumptions on cultivation parameters differed only where the characteristics of the strategies varied, e.g. in terms of PPP use (see Section 2.1.2), amount of direct payments (Swiss agricultural subsidies which are subject to environmental cross-compliance),[1] estimated yield and prices per kg apple, storage loss, irrigation, fertilization and the use of additional nets, covers or machinery (Table 1).

«PEP2018»: This strategy was created as a reference and represents a common Swiss integrated apple production system in 2018 according to the PEP guidelines and good agricultural practice. In this strategy, crop protection is mainly based on PPPs with synthetic active ingredients. The scab-susceptible variety "Gala" was chosen because it is the most commonly grown variety in Switzerland (BLW, 2018). The standard assumption here was 2222 trees per hectare. Irrigation systems were not considered for the «PEP2018» strategy, as this is not standard in many regions of Switzerland. Fertilization was carried out according to the guidelines of PEP (Table 1). An annual yield of 38 t/ha was assumed, which corresponds to an average yield from 2008 to 2017 (SOV, 2018a). For the «PEP2018» strategy, the proportion of 1st class apples was set at 75% (based on typical proportions ranging between 60 and 90% for Gala according to (Bravin and Kilchenmann, 2012)). Due to storage, a loss of 10% was assumed (Good et al., 2012). The price of 1st class apples was set at 1.05 CHF[2]/kg, the price of 2nd class apples at 0.45 CHF/kg (SOV, 2018b). The application of this strategy entitles to receive direct payments under the PEP (complying with environmental cross-compliance) of 1300 CHF/ha/year (BLW, 2021b).

«PPP Reduced»: The aim of this strategy was to minimize the use of PPPs of synthetic origin and possible residues on the apples but to maintain the yield in an integrated production system. To reduce the PPP use, various alternative measures were combined, such as the use of a scab-resistant apple variety (Bonita), the implementation of mechanical instead of chemical weed control, use of a rain cover to reduce the risk of fungal infections, installation of a fine-meshed net to protect the

[1] Swiss farmers are entitled to direct payments from the Swiss Confederation if they comply with the "Proof of Ecological Performance", which includes, criteria on fertilizers, animal welfare, set-aside for biodiversity and certain restrictions on PPP use (e.g. for apple orchards see SAIO, 2018).

[2] 1.0 Swiss franc (CHF) corresponds to approximately 0.96 euros or 1.07 dollars (January 2022).

apples from insects, and additionally the use of biological control. Due to the use of a rain cover, the installation of a drip irrigation system was assumed. Data for fertilization, yields, proportion of 1st class apples, storage losses and apple prices were determined to be identical to «PEP2018». However, the strategy «PPP Reduced» received additional direct payments for compliance with a program to avoid herbicides and certain fungicides with a high risk potential (+800 CHF/ha/year compared to the «PEP2018» strategy).

«High Yield»: The aim of this strategy was to achieve maximum yields in a conventional production system, thus, PPPs with maximum effectiveness to keep yield risks as low as possible were adopted. This strategy does not qualify for direct payments linked to environmental cross-compliance and additional restrictions in the PEP guidelines on the use of fertilizer and PPPs do not apply. Compared to the «PEP2018» strategy, twice the amount of fertilizer and a 50% higher number of trees per hectare were assumed, resulting in 3333 trees/ha. This allows an increase in yield to 60 t/ha with a 90% share of 1st class apples, according to experts (SI Table S2) and based on unpublished data. For this strategy, the installation of two irrigation systems was assumed: a drip irrigation to increase yields and an overhead sprinkler to protect against frost and extreme heat. Finally, it was assumed that the prices of apples do not differ from the prices in the «PEP2018» strategy.

«Organic»: This strategy should reflect an average certified organic apple production in Switzerland using the most commonly organic grown apple variety Gala. The organic guidelines prohibit the use of PPPs of synthetic origin and mineral fertilizer. Therefore, it was assumed, that only organic fertilizer and only PPPs from organic origin are used. According to Fricke et al. (2009), a 35% lower yield with the same amount of trees (2222 trees/ha) was assumed for the organic apples compared to the «PEP2018» strategy.

Since it is known that consumers are willing to pay more for organic apples and also accept apples that are slightly imperfect in appearance, the same proportion of 1st class apples but with more than doubled price was assumed in comparison to the «PEP2018» strategy (Bio Suisse, 2018a). As 2nd class organic apples are mainly sold as apples for industrial processing and not as dessert apples, their price was assumed to be one fourth lower than in the «PEP2018» strategy (Bio Suisse, 2018b). A double storage loss compared to «PEP2018» was taken into account, as there is no chemical treatment against storage diseases (Good et al., 2012). Finally, farmers receive additional direct payments for the organic cultivation of apples (+1600 CHF/ha/year compared to the «PEP2018» strategy) (BLW, 2021b).

2.1.2. Spray sequences

The «PEP2018» reference strategy was created on the basis of the PPP use data of the Agri-Environmental Indicators (AEI) farm-network from 2013 to 2015 (de Baan et al., 2015). First, the median number of interventions in apple orchards per pesticide type, i.e. herbicides, fungicides (incl. bactericides), insecticides, and plant growth regulators, was taken as an average treatment intensity under average damage pressure (SI Table S1). Subsequently, the most frequently used active ingredients were selected for each pesticide type and time of application. Then, for each active ingredient and the respective indication, a frequently used product including its application rate was selected. Finally, the spray sequence of the reference strategy was discussed with experts (SI Table S2) in order to fill data gaps and to obtain a representative spray sequence that could be applied in this way in apple orchards. The spray sequences of the other three strategies were defined by replacing, adding or removing products or by changing the application rate (s) from the original spray sequence of the «PEP2018» strategy. To ensure their suitability, the final spray sequences were also discussed with experts. The selected active ingredients, the respective product application rates and number of treatments are shown in SI Table S3.

«PEP2018»: According to the AEI data set, a median of 16 fungicide interventions (including bactericides) was reported on apple orchards, mainly against scab, powdery mildew, storage diseases and fire blight. To define the «PEP2018» strategy, altogether ten different fungicidal active ingredients that were most often used were selected including two fungicides approved for use in organic farming (Table 1). Although both, captan and folpet, were approximately equally used based on these data, the spray sequence was only calculated with captan, as a combined use hardly ever occurs. Moreover, a median of five insecticide interventions to control the apple sawfly (*Hoplocampa testudinea*), various aphids and the codling moth (*Cydia pomonella*) was reported in the data set. Thus, the five most often used insecticidal active ingredients were selected including one substance approved for use in organic farming. Additionally, a median of two herbicide applications was recorded in the AEI data set. However, as experts (see SI Table S2) indicated that three applications in the tree rows (i.e. directly under the trees, which corresponds to about one third of the orchard area) is the standard, an additional treatment was assumed. In addition, according to experts, every four years a herbicide is also applied in the inter-rows (i.e. the driving lanes of the orchards). Thus, the five most often used herbicides were selected for use in four applications. Finally, one application containing two plant growth regulators for chemical thinning was assumed for the spray sequence of the «PEP2018» strategy based on the AEI data set.

«PPP Reduced»: Compared to the spray sequence of the «PEP2018» strategy, nine fewer fungicide or bactericide applications were assumed in the «PPP Reduced» strategy (SI Table S3), which is due to the use of a robust variety, rain cover and biological control. In the first half of the season, the use of synthetic PPP (with four active ingredients) was assumed, while in the second half of the season (where the risk of fungal infection is generally lower), fungicide products (with two active ingredients) were chosen that were approved in organic farming. Compared to the spray sequence of the «PEP2018» strategy, two insecticide treatments were omitted and an insect net, pheromones and granuloviruses were used instead. In addition, the active ingredient chlorpyrifos-methyl was replaced by acetamiprid and pirimicarb by spirotetramat. It was assumed that in the «PPP Reduced» strategy no herbicides are used and the weeds are controlled mechanically. In total, five products containing living organisms or viruses (such as the fungus *Aurobasidium pullulans* or granuloviruses) were chosen as substitutes for synthetic insecticides and bactericides.

«High Yield»: The number of treatments and the fungicide active ingredients were assumed to be the same compared to the spray sequence of the «PEP2018» strategy (SI Table S3). However, sulphur was assumed to be added nine times instead of four times to a tank mixture with other fungicides, which would not be allowed under PEP guidelines. Compared to the spray sequence of the «PEP2018» reference strategy, three additional insecticide treatments with three different active ingredients were assumed. Moreover, a 1.6 times higher application rate was chosen for paraffin oil to be effective against additional pests. The application of an additional herbicide with a different active ingredient was assumed, as well as a 3.2-fold increase in the application rate of a glyphosate application to control not only annual but also perennial herbs.

«Organic»: No PPP of synthetic origin was included in the «Organic» strategy. However, since the same number of fungicide treatments was supposed to be necessary compared to the spray sequence of the «PEP2018» reference strategy, the application of five different active ingredients approved for use in organic farming was assumed (SI Table S3). Moreover, two insecticide treatments could be omitted and the remaining applications contained three active ingredients approved for use in organic farming. The use of herbicides and plant growth regulators were not assumed in this spray sequence and were replaced by mechanical weed control and manual thinning. However, as within the spray sequence of the «PPP Reduced» strategy, five PPP containing living organisms or viruses such as the fungus *A. pullulans* or granuloseviruses were chosen as substitutes for synthetic insecticides and bactericides.

2.2. Assessment indicators

For each of the four aspects assessed (PPP use, local ecotoxicological risks, global environmental impacts and economic impacts), we selected the most important indicators for this multi-criteria assessment. This resulted in a total of 13 indicators.

2.2.1. PPP use

The **treatment frequency index** (TFI) was chosen to describe PPP use taking into account both the number of product applications and the dosage applied relative to a standard dose. The TFI was calculated by dividing the assumed application rate of each product by the approved standard doses of the product. The ratios of all products defined for use were then summarised to one TFI per strategy. The approved standard dose of each product was derived from the Swiss Index of Phytosanitary Products (BLW, 2018), calculated for a standard water volume of 1600 l/ha. If an approved standard dose was given as a range, the maximum dose was used to calculate the TFI. For the herbicides, the dose assumed to be applied was in most cases lower than the standard dose, as it was assumed that herbicides were only applied directly in the tree rows and not on the whole area of the orchards. PPPs containing living organisms or viruses (e.g. *A. pullulans* against fire blight, granulovirus against codling moth or summer fruit tortrix moth) and pheromone sticks were not included in the TFI. In contrast to the number of PPP treatments given in Table 1, the TFI assesses each product separately, regardless of whether it is mixed with other products and sprayed simultaneously (a common practice in orchards) or applied individually.

2.2.2. Local ecotoxicological risk

The model SYNOPS (Gutsche and Strassemeyer, 2007; Strassemeyer et al., 2017) was used to calculate three different indicators: the **local ecotoxicological risk** of PPP on organisms living in edge-of-field **surface waters**, **agricultural soils** and terrestrial **off-crop habitat**. The risk to organisms of these habitats is usually also assessed in the ecotoxicological risk assessment as part of product authorization (European Commission, 2002). The risks were modeled using Swiss environmental conditions as described elsewhere (de Baan, 2020; Waldvogel et al., 2018; for further details see SI). SYNOPS enables the risk assessment of entire spraying sequences applied in a field. Thus, for each PPP application, a predicted environmental concentration (PEC) was calculated for each environmental compartment, taking into account environmental and application parameters as well as physico-chemical properties of the applied active ingredients. The risk potential was calculated for each environmental compartment as the Exposure-Toxicity-Ratio, which is the ratio between the PEC value and the toxicity of an active ingredient in an environmental compartment. For surface waters, chronic and acute effects on fish, daphnids and benthic chironomid larvae and acute effects on unicellular algae and the common duckweed *Lemna gibba* were considered. For agricultural soils, the chronic effects on earthworms and springtails were assessed. For off-crop habitat, acute effects on predatory mites, parasitoid wasps and honeybees were considered. The ecotoxicological endpoints of the organisms studied were taken from the pesticide property database (Lewis et al., 2016). A quality check of these data was carried out by an ecotoxicology expert (see SI Table S2) and 15 endpoints were adjusted because a new or more scientifically sound study was available (see SI Table S7). The risk potentials were finally aggregated over a spray sequence by evaluating the maximum risk of the most sensitive species predicted within one year. To assess the risk of a spray sequence, the effects of mixtures of several active ingredients applied, temporal dynamics as well as product-specific mandatory risk mitigation measures (e.g. minimal distance to surface water) were considered. To assess the risk potential caused by individual active ingredients in each of the three environmental compartments, an analysis of their maximum risk potential was carried out, without considering the effects of mixtures.

2.2.3. Global environmental impacts

Global environmental impacts were analyzed using the Swiss Agricultural Life Cycle Assessment method SALCA (Gaillard and Nemecek, 2009; Nemecek et al., 2010). The indicators freshwater ecotoxicity, eutrophication potential, resource use, global warming potential and biodiversity were selected because they are representative for the most important environmental impacts of agricultural crop production (Nemecek et al., 2011). The SALCA method includes a database of life cycle inventories with a focus on agriculture (including the ecoinvent database v3 (Wernet et al., 2016)), models for calculating the main direct emission from the field or farm and various methods for impact assessment (Bystricky et al., 2014; Bystricky et al., 2020; Nemecek et al., 2010). Environmental impacts were calculated for a functional unit, which was defined as 1 kg of 1st class apples remaining after a 6-month storage period (kg $apple_{1st}$). Economic allocation was used to subtract the environmental impact associated with producing 2nd class apples on the same plantation (see SI). A few processes were missing in the life cycle inventory databases and have therefore been assembled (see SI Tables S6–S9).

The direct field emissions of eutrophying substances, greenhouse gases and heavy metals was calculated using SALCA. Direct field emissions of all PPPs except heavy metals were calculated using the PestLCI consensus model (Dijkman et al., 2012; Gentil-Sergent et al., 2021; Nemecek et al., 2020). The impacts on freshwater ecotoxicity, eutrophication potential, resource use and global warming potential were finally calculated using the software SimaPro 9.0.0.47 (Simapro 2019).

The **freshwater ecotoxicity** for all chemicals emitted during the life cycle of apple production (including PPPs, fertilizers, fuel combustion, industrial production of inputs and machinery, etc.) was calculated using the impact assessment method USEtox 2.02 (Rosenbaum et al., 2008). Impacts are calculated on a continental scale, as emissions can occur in different regions (e.g. fuels burnt during transport are not emitted into the habitat next to the field; for further differences between freshwater ecotoxicity and local ecotoxicological risk see SI Table S14). The characterization factors for metals were adapted to Swiss conditions (SI Table S13) and missing characterization factors for additional active ingredients important for this study were derived (see SI Table S12). The **global warming potential (GWP)** was calculated using the method of IPCC (2013). The GWP is expressed in CO_2-equivanents (CO_2-eq) and has a 100-year time horizon. The **resource use** of the different strategies was assessed using the method cumulative exergy demand (CExD) (Alvarenga et al., 2013; Bösch et al., 2007). This method takes into account the use of different types of resources (fossil fuels, metals, minerals, land) and gives the usable energy of resources in the unit MJex. The **eutrophication potential** was calculated with the method EDIP2003 (Hauschild and Potting, 2005). The aquatic and terrestrial eutrophication potential of N- and P-compounds were combined into one indicator, expressed as an eutrophication potential normalized for Switzerland (i.e. compared to the average eutrophication potential per person in Switzerland).

For the assessment of **biodiversity**, the life cycle inventory and impact assessment were carried out separately using the SALCA biodiversity model (Jeanneret et al., 2009; Jeanneret et al., 2014; Van der Meer et al., 2017). This method evaluates the effect of management measures on terrestrial biodiversity of eleven indicator species in the field (in-crop), covering plants, vertebrates and invertebrates. A biodiversity score is calculated that expresses the biodiversity status of a field under a particular management. To assess how different crop protection strategies affect biodiversity, the biodiversity scores of each strategy were confronted to the biodiversity score of an alternative land use (Koellner et al., 2013), i.e. the biodiversity that would hypothetically be present if the apple orchard was abandoned. In Switzerland, abandoned apple orchards would most likely be used as arable land, which was assumed as alternative land use. This finally resulted in a biodiversity score per hectare for each strategy. To determine the biodiversity impact per kg apples, the area used to produce 1 kg apple was multiplied by this biodiversity score per ha. Positive values represent an advantage for biodiversity compared to the alternative land use, negative values a negative impact. Further details on the LCA methods and input data are shown in the SI.

2.2.4. Economic impacts

As economic sustainability indicators, profitability (farmer's hourly wage), production risks (yield fluctuations) and financial autonomy (invested capital) we selected according to Mouron et al. (2012). In addition, workload (labor input) was assessed, because available workforce can be a limiting factor at the farm scale (Lechenet et al., 2014). A full cost calculation of an average yield year and a cash-flow calculation of the entire life of an apple orchard (15 years, as described above) were carried out using the software Arbokost, an economic farm management software tool developed for Swiss fruit growers (Bravin and Kilchmann, 2009). Costs include all direct costs for machines, materials, interest and salaries of the employed staff as well as indirect costs, such as building costs. For the revenues, the sale of apples and direct payments were taken into account. A change of markets and prices during the 15-year period was not considered. An interest rate of 2.5% was assumed for invested capital. It was assumed that all work is done by family members, except for harvesting and thinning, where 80% of the labor is made by external workers, who receive a salary of 21 CHF/h.

The **farmer's hourly wage** [in CHF/h] provides information on the average hourly wage of the family members for the work invested in the apple orchard. It was calculated by subtracting the costs [CHF/ha/year] from the revenue [CHF/ha/year] and then dividing by the labor input of all family members (referred to as internal workforce) [h/ha].

The **invested capital** [CHF/ha] includes the actual construction costs for the apple orchard (e.g. planting material, nets, use of machinery, labor and material costs for the construction of the orchard) as well as the deficit during the first three years (development phase), when yields and revenues are lower than the costs.

The **labor input** [h/ha] takes into account the total time required for all activities involved in the maintenance and harvesting of 1 ha of an apple orchard (e.g. fertilizing, plant protection incl. pest monitoring, opening and closing of nets, administration). No distinction was made between family members and contract workers.

Experts (see SI Table S2) estimated the **yield fluctuations** in relation to the «PEP2018» reference strategy, as quantitative data for Switzerland were not available for all assessed strategies. This indicator describes predominantly the risk for yield losses in years with high pest or damage pressure.

2.3. Multi-criteria assessment

To facilitate the interpretation of the results of the 13 indicators assessed and to illustrate the overall performance of the crop protection strategies, a multi-criteria assessment was carried out. In a first step, the relative difference (in %) between the indicator results *I* of the different strategies *s* compared to the reference *ref* was calculated as follows:

$$\text{Relative difference } (\%) = (\mathrm{I_S} - \mathrm{I_{ref}})/\mathrm{I_{ref}} * 100.$$

For each indicator, a second step classified which relative difference in indicator results led to a much better, better, similar, worse or much worse performance of a strategy. The size of the classes was defined separately for each indicator, with indicators with higher uncertainty or more variable outcomes (e.g. local ecotoxicological risks) receiving broader classes than indicators with less variable outcomes (e.g. farmer's hourly wage) (Table 2). The categories for the relative comparison were chosen in reverse order for some indicators in order to consider negative and positive effects in the same way and to make the results independent of the choice of the reference system (Mouron et al., 2012). For the local ecotoxicological risk indicators, the categories defined by Mouron et al. (2012) were used; for the indicators used to assess the global environmental impacts, the categories were defined according to Nemecek et al. (2005). For the indicators on PPP use, biodiversity and economics, the categories were created by experts in these methods.

2.4. Sensitivity analyses

To test the influence of parameters with high uncertainty and high expected effects on the indicator results, several sensitivity analyses were conducted. To assess the PPP use, the TFI was analyzed using different standard dosages: instead of the maximum approved application rate, the median and minimum approved rate were used. To assess the local ecotoxicological risks, several sensitivity analyses with alternative active ingredients in the spray sequences or additional treatments were tested: In the spray sequences of the «PEP2018» reference strategy and the high-yield strategy, chlorpyrifos-methyl was replaced by acetamiprid, as the approval of chlorpyrifos-methyl in apple orchards was withdrawn in 2019. In a further sensitivity analysis, captan was replaced by folpet in the spray sequence of the «PEP2018» strategy, as both active ingredients are often used in Swiss apple orchards, but their use is mutually exclusive. To assess the ecotoxicological risks of the «Organic» strategy, an unfavorable year with twice as many fungicide interventions was analyzed. In addition, an alternative «Organic robust» strategy was evaluated with the robust apple variety "Bonita".

To assess the global environmental impacts, the choice of the functional unit is very decisive. Thus, the indicators were additionally calculated in terms of the area [ha*year]. In addition, a separate assessment of metallic and organic substances was carried out with regard to the freshwater toxicity. For biodiversity, results were analyzed using an alternative reference land use (species-rich grassland instead of arable land).

For the economic evaluation, the sensitivity of the farmer's hourly wage on prices for 1st class apples was analyzed for the «PPP Reduced» strategy and the «High Yield» strategy, as there is currently no specific market for these strategies and forecasts for future prices are uncertain. Firstly, the prices for the «High Yield» strategy were varied in order to determine at which price for 1st class apples the farmer's hourly wage would be equal to that of the reference strategy «PEP2018» or even reach a zero wage. On the other hand, it was calculated how a 55% higher price for apples produced under the «PPP Reduced» strategy

Table 2
Translation of indicator results into a relative comparison with a reference strategy. Values are indicated in %.

	PPP use intensity	Local ecotoxicological risk	Global environmental impacts				Farm economics	
	Treatment frequency index	Surface water, soil, off-crop habitat	Ressource use, global warming potential	Eutrophication potential	Freshwater ecotoxicity	Biodiversity	Farmer's hourly wage	Invested capital, labor input
Much worse	>100	>1233	>50	>100	>150	<−13	<−29	>40
Worse	33 to 100	33 to 1233	17 to 50	33 to 100	50 to 150	−13 to −5	−29 to −9	10 to 40
Similar	−25 to +33	−25 to +33	−14 to +17	−25 to +33	−33 to +50	−5 to +5	−9 to +10	−9 to +10
Better	−50 to −25	−92 to −25	−33 to −14	−50 to −25	−60 to −33	5 to 15	10 to 40	−29 to −9
Much better	<−50	<−92	<−33	<−50	<−60	>15	>40	<−29

(an amount that lies between the prices paid for conventionally and organically grown apples) would affect the farmer's hourly wage.

3. Results

3.1. PPP use

The «PEP2018» reference strategy had a TFI of 30.1 (Fig. 1). The TFI of the «PPP Reduced» strategy and the «Organic» strategy was 67% and 53% lower than the «PEP2018» strategy, respectively, while the «High Yield» strategy had a 22% higher TFI compared to the «PEP2018» strategy. Fungicides contributed to the total TFI by 64–84% and insecticides by 15–23%. Herbicide applications were only part of the «PEP2018» and «High Yield» strategies and contributed to 7% and 10% of the TFI, respectively. Plant growth regulators contributed to 3–13% of the TFI for the non-organic strategies.

3.2. Local ecotoxicolocigal risks

3.2.1. Surface water

The strategies «PPP Reduced» and «Organic» resulted in a significantly lower local risk in surface waters compared to the «PEP2018» reference strategy (−99% and −98%, respectively), while the strategy «High Yield» showed similar risks (+0.1%; Fig. 2A). In the «PEP2018» and «High Yield» strategies, the active ingredient chlorpyrifos-methyl dominated the risks in surface waters, followed by diuron and 2,4-D (Fig. 2D). In the strategy «PPP Reduced», acetamiprid was the dominant active ingredient, although at a much lower risk than for «PEP2018», followed by captan and dithianon (Fig. 2D). In the «Organic» strategy, aluminium sulphate was responsible for the largest share of the risk, followed by azadirachtin and copper oxychloride.

3.2.2. Soil

The risks in the soil compartment were 98% lower for the «PPP Reduced» and «Organic» strategies and similar for the «High Yield» strategy (+1%) compared to the «PEP2018» strategy (Fig. 2B). In the «PEP2018» and «High Yield» strategies, risks in the soil compartment were clearly dominated by chlorpyrifos-methyl, followed by thiacloprid and difenoconazole (SI, Fig. S3). The «PPP Reduced» and «Organic» strategy shared the same risk-dominant substance in soils, i.e., paraffin oil, which was followed by captan and dithianon in the «PPP Reduced» strategy and by aluminium sulphate and azadirachtin in the «Organic» strategy. The five risk-dominating substances in all strategies were either insecticides or fungicides (SI, Fig. S3).

3.2.3. Terrestrial off-crop habitats

The «PPP Reduced» and «High Yield» strategies showed a higher risk for terrestrial off-crop habitats (+88% and +70%, respectively), while the «Organic» strategy showed a lower risk than the «PEP2018» reference strategy (−93%; Fig. 2C). In the «PEP2018» strategy, chlorpyrifos-methyl dominated the risks, followed by indoxacarb and thiacloprid. In the «PPP Reduced» strategy, the risk-dominant substances were spirotetramat, acetamiprid and sulphur (SI Fig. S4). While in the «High Yield» strategy the risks for the off-crop habitats were induced by spinetoram, chlorpyrifos-methly and thiacloprid, in the «Organic» strategy aluminium sulphate, sulphur and azadirachtin were the risk-dominating substances. In all strategies, the five substances with highest risks were insecticides and fungicides (SI Fig. S4).

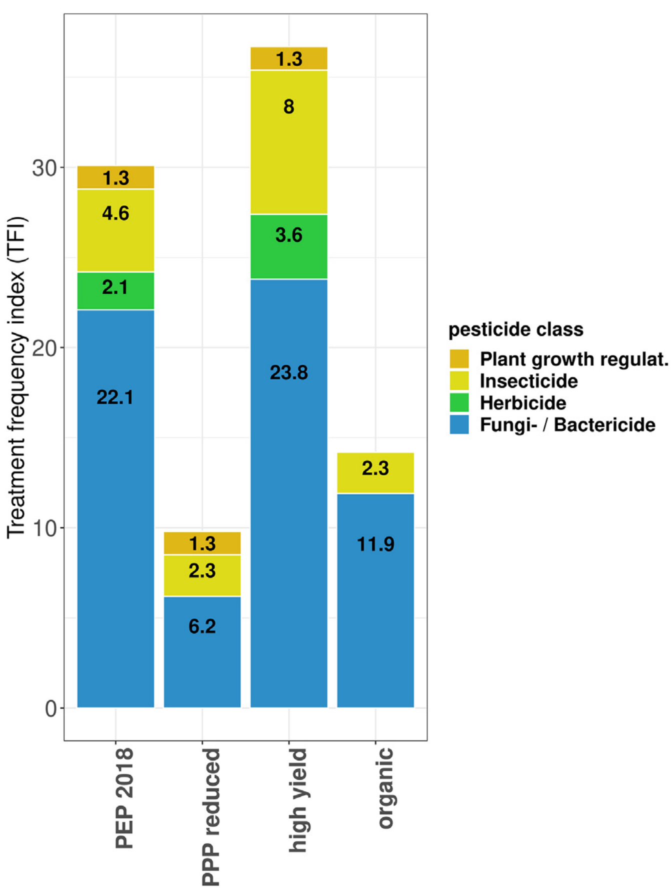

Fig. 1. Treatment frequency index (TFI) of the four crop protection strategies separated by different pesticide types. «PEP2018»: average integrated strategy in 2018 based mainly on the use of synthetic PPP; «PPP Reduced»: integrated strategy with reduced PPP use and low residues but without yield losses; «High Yield»: conventional strategy with the aim of maximizing yields; «Organic»: average organic production in 2018.

3.3. Global environmental impact

3.3.1. Freshwater ecotoxicity

The strategies «PPP Reduced» and «High Yield» showed a 76% and 26% lower freshwater ecotoxicity per kg $apple_{1st}$, respectively, compared to the «PEP2018» strategy, while the «Organic» strategy showed an 18% higher freshwater ecotoxicity (Fig. 3A).

For all strategies except «PPP Reduced», PPPs were the most important driver of freshwater ecotoxicity with a share between 63%–80%, while other substances (e.g., metals such as strontium, zinc or cadmium from fertilizer applications) only made a smaller but still relevant contribution. The active ingredient with the highest contribution to freshwater ecotoxicity was copper with a share of 80% in the «Organic» strategy, 50% in the «PEP2018» strategy and 40% in the «High Yield» strategy; copper was not included in the spray sequence of the «PPP Reduced» strategy. Synthetic pesticides were responsible for 30%, 25% and 14% of freshwater ecotoxicity in the «PEP2018», «High Yield» and «PPP Reduced» strategies, respectively. The most relevant synthetic pesticides for the freshwater ecotoxicity were captan, diuron and dithianon.

3.3.2. Global warming potential

The strategies «PPP Reduced», «High Yield», and «Organic» resulted in a higher global warming potential (GWP) per kg $apple_{1st}$ of 21%; 14%, and 38%, respectively, compared to the «PEP2018» reference strategy (Fig. 3B). The most important contributions to GWP were machine use (17–34%), nets and covers (11–31%), field emissions (9–20%) and storage (12–15%). To a smaller extent, also the production of PPP and fertilizer added to the GWP of the different strategies (1–7% and 0–11%, respectively). For the «PPP Reduced» and «High Yield» strategies, irrigation accounted for up to 5 and 24% of the GWP, respectively. Finally, the hot water treatment as part of the «Organic» strategy contributed to 13% of the GWP, while the additional insect net and rain cover accounted for up to 14% of the GWP of the «PPP Reduced» strategy.

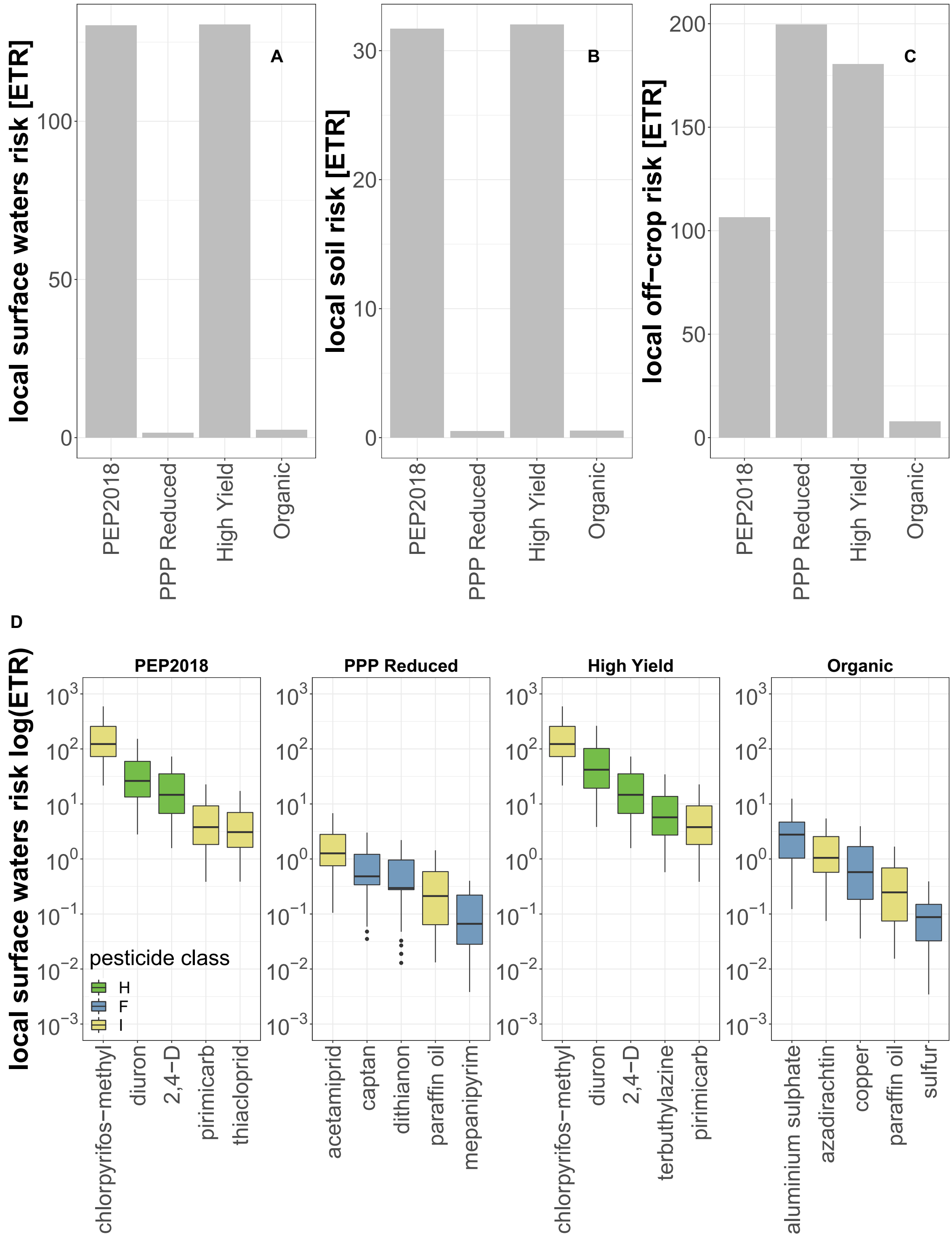

Fig. 2. The local ecotoxicological risks for surface waters (A), soil (B) and for the terrestrial off-crop habitat (C) are shown for the four strategies «PEP2018», «PPP Reduced», «High Yield» and «Organic». For surface waters, the five risk-dominating substances per strategy are also shown (D). H = herbicides, F = fungicides, I = insecticides. «PEP2018»: average integrated strategy in 2018 based mainly on the use of synthetic PPP; «PPP Reduced»: integrated strategy with reduced PPP use and low residues but without yield losses; «High Yield»: conventional strategy with the aim of maximizing yields; «Organic»: average organic production in 2018.

Compared to all other strategies, the «Organic» strategy resulted in the highest GWP per kg apple$_{1st}$ mainly because of the lower yields, the use of machinery (for harvesting, mechanical weeding, and PPP application), the hot-water post-harvest treatment, and the use of hail nets (installation, fuels combusted during opening and closing, waste disposal). However, direct field emissions mainly caused by the use of fertilizers were lower in the «Organic» strategy but highest in the «High Yield» strategy.

3.3.3. Resource use (exergy)

The resource use per kg apple$_{1st}$ of the strategies «PPP Reduced» and «Organic» was 12% and 81% higher, respectively, than in the «PEP2018» strategy, whereas the resource use of the «High Yield» strategy was 32% lower (Fig. 3C). The orchard itself, i.e., the area needed to produce one kg apple$_{1st}$, contributed most to the resource use with 60–75%. While nets and covers accounted for up to 9–20%, and storage for up to 8–16% to the resource use. Machinery and production of fertilizer and

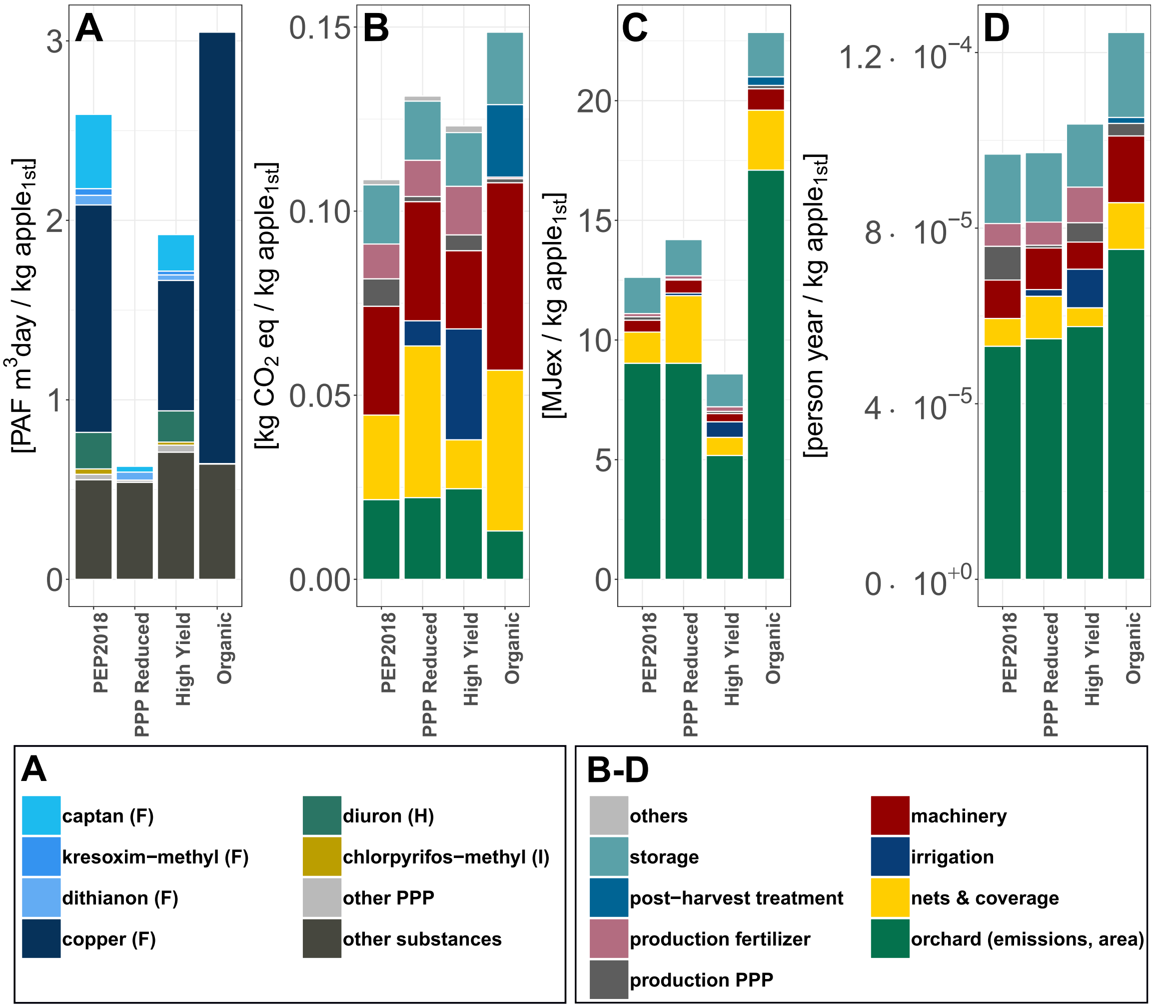

Fig. 3. The following indicators for global environmental impacts are shown for all four strategies. (A) Freshwater ecotoxicity (whereas PAF is the potentially affected fraction of species per kg apple$_{1st}$), (B) Global Warming Potential, (C) Resource use, and (D) Eutrophication potential. Please note that the color code for figure A is different from that for figures B–D. «PEP2018»: average integrated strategy in 2018 based mainly on the use of synthetic PPP; «PPP Reduced»: integrated strategy with reduced PPP use and low residues but without yield losses; «High Yield»: conventional strategy with the aim of maximizing yields; «Organic»: average organic production in 2018.

PPP only added to the resource use by 4%, 1.0–2.2% and 0.3–1.2%, respectively. In addition, the energy consumption of irrigation accounted for 1 and 8% of the resource use in the «PPP Reduced» and «High Yields» strategies, respectively. The energy use of the post-harvest treatment in the «Organic» strategy accounted for 2% of the resource use. Thus, the main contributors to the cumulative exergy demand in all strategies were land resources (69–84%), followed by non-renewable energy (13–26%), renewable energy (3–4%), and metals and minerals (0.3–0.7%).

3.3.4. Eutrophication potential

The «PEP2018» reference strategy had the lowest eutrophication potential per kg apple$_{1st}$ compared to all other strategies («PPP Reduced»: +0.4%; «High Yield»: +7.2%, «Organic»: +28.7%; Fig. 3D). The largest contribution to the eutrophication potential was from orchard emissions (55–60%, mainly from fertilizer use and soil erosion), followed by storage (14–16%), machinery use (6–12%), nets and covers (4–10%), and by the production of fertilizer (0–8%) and PPP (1–8%). The irrigation in the strategies «PPP Reduced» and «High Yield» added to 2% and 8% to the eutrophication potential, respectively. In addition, the use of fertilizer had a slightly higher impact on the eutrophication potential of the «High Yield» strategy.

In terms of nutrients, phosphate accounted for most of the eutrophication potential (38–60%), followed by ammonia (9–23%), nitrogen oxides (12–17%) and phosphorus (7–18%). Nitrate was only relevant for the «High Yield» strategy and contributed 17% to its eutrophication potential.

3.3.5. Terrestrial biodiversity (in-crop)

The differences between the biodiversity score per hectare of the four strategies were only small and ranged from 15.5 («PEP2018») to 15.7 («High Yield») to 16.6 («PPP Reduced», «Organic»; Table 3). However, all strategies had a biodiversity score that was more than twice as high as the biodiversity score of the reference land use (average Swiss cropland with a score of 7.6), but lower than an extensively used grassland (21.3). Calculated per kg apple$_{1st}$ instead of per ha, the biodiversity impact scores indicated a beneficial effect on biodiversity of all four strategies. Compared to the «PEP2018» reference strategy,

Table 3
Biodiversity scores and biodiversity impact scores of the four strategies. «PEP2018»: average integrated strategy in 2018 based mainly on the use of synthetic PPP; «PPP Reduced»: integrated strategy with reduced PPP use and low residues but without yield losses; «High Yield»: conventional strategy with the aim of maximizing yields; «Organic»: average organic production in 2018.

	«PEP2018»	«PPP Reduced»	«High Yield»	«Organic»
Biodiversity score/ha	15.5	16.6	15.7	16.6
Biodiversity impact score/kg apple$_{1st}$	2.27	2.59	1.61	4.88

«PPP Reduced» showed a 14% higher positive impact on biodiversity, while «High Yield» showed a 29% lower positive impact on biodiversity. The highest positive impact on biodiversity was obtained by the «Organic» strategy (+115% compared to the «PEP2018» strategy).

Of the eleven indicator species groups analyzed, grassland flora, arable crop flora and small mammals had the highest biodiversity values per hectare (see SI Table S15). The greatest differences between the strategies were found in the arable crop and grassland flora and in the birds in the inter-rows (i.e. driving lanes) and orchard habitats.

3.4. Economic impact

3.4.1. Farmer's hourly wage

The farmer's hourly wage of the «PEP2018» strategy was calculated at 15 CHF/h. It was lower for the strategy «PPP Reduced» (−172%), but higher for the strategies «High Yield» (+111%) and «Organic» (+141%; Table 4). In the «PPP Reduced» strategy, the farmer's hourly wage was negative due to the high costs and the low revenue.

Table 4
Full cost analysis, analysis of revenues and costs and yield fluctuations related to one ha of apples produced in Switzerland for different plant protection strategies assuming a 15 year life-span of orchards. «PEP2018»: average integrated strategy in 2018 based mainly on the use of synthetic PPP; «PPP Reduced»: integrated strategy with reduced PPP use and low residues but without yield losses; «High Yield»: conventional strategy with the aim of maximizing yields; «Organic»: average organic production in 2018. The selected economic indicators are marked with an asterisk.

	«PEP 2018»	«PPP Reduced»	«High Yield»	«Organic»
Revenue (CHF/ha/yr)				
Apples class I	26,933	26,933	51,030	32,604
Apples class II	3848	3848	2430	1630
Direct payments	1300	2100	–	2900
Total revenue	32,080	32,880	53,460	37,134
Costs (CHF/ha/yr)				
Fertilization	176	176	355	178
Plant protection	2720	2279	3521	2610
Irrigation	–	600	4600	–
Machinery	4493	6191	5742	5561
Pruning (external workers)	1680	1680	1680	1848
Harvesting (external workers)	5320	5320	8400	2421
Interest (imputed)	1961	3084	2349	2077
Depreciation of invested capital	7225	13,465	9385	7874
Price deductions (e.g., sorting cost)	3473	3523	5210	3885
Diverse costs	300	300	300	300
Total costs	27,348	37,033	41,543	26,752
Farm enterprise income (CHF/ha/yr)	4732	−3738	11,917	10,382
Farmer's hourly wage (CHF/h) *	15	−11	32	37
Invested capital (CHF/ha)				
Orchard (incl. trees)	32,307	32,307	41,470	40,084
Hail net	27,803	27,803	27,803	27,803
Insect net	–	8892	–	–
Rain cover	–	53,982	–	–
Irrigation system	–	12,000	16,750	–
Maintainance (year 1–3)	26,595	26,595	26,595	26,595
Total invested capital *	86,706	161,580	112,619	94,483
Labor input (h/ha/yr)				
Internal (unpaid) workforce				
Fertilization	3	3	4	1
Plant protection	43	44	46	51
Training	120	120	120	120
Pruning (manual) + maintanance	20	20	21	22
Opening/closing nets	20	40	20	20
Irrigation	–	14	21	–
Harvesting	63	63	100	29
Administration	40	40	40	40
Total internal (unpaid) workforce	309	344	372	283
External (paid) workforce				
Pruning (manual)	80	80	80	88
Harvesting	253	253	400	115
Total external (paid) workforce	333	333	480	203
Total labor input *	643	677	852	486
Yield fluctuation *	Average	Higher	Lower	Higher

For the «PEP2018» strategy, the total annual **costs** were calculated at 27,348 CHF/ha/year, which is comparable to the costs to be spent for the «Organic» strategy (−2%). However, the costs were much higher for the «PPP Reduced» and «High Yield» strategies (+34% and +52%, respectively; Table 4). The highest costs were the depreciation of invested capital (between 23 and 37% of total costs, depending on the strategy), machinery (14–21%), harvesting (9–20%), price deductions (e.g., sorting cost, labelling costs, marketing, post-harvest hot water treatment: 10–15%), pruning (4–7%), plant protection (6–10%), interest rates (6–8%) and fertilization (0–1%). The costs of operating the irrigation accounted for 2 and 11%, respectively, for the strategies «PPP Reduced» and «High Yield».

The **revenue** of the «PEP2018» strategy was calculated at 32,080 CHF/ha/year, which is comparable to the revenue to be achieved in the «PPP Reduced» strategy (+2%). Even higher revenues can be achieved by the strategies «High Yield» and «Organic» (+67% and +16%, respectively). The revenue consisted mainly of 1st class apple sales (between 82 and 95%, depending on the strategy), 2nd class apple sales (4–12%) and the revenue due to direct payments (0–8%).

3.4.2. Invested capital

A total invested capital of 86,706 CHF/ha was calculated for the «PEP2018» reference strategy. All other strategies required higher investments (+86% for «PPP Reduced»; +30% for «High Yield»; +9% for «Organic»; Table 4). The total invested capital consisted mainly of the construction of the orchard (including purchasing and planting the trees), which represented between 20 and 42% of the invested capital, the installation of a hail net (17–32%) and the maintenance of the orchard during the first three years, when no or only low yields are expected (16–31%). For the «PPP Reduced» strategy, additional investments were required for the installation of the rain cover (53,982 CHF/ha), the insect net (8892 CHF/ha) and the irrigation system (12,000 CHF/ha). For the «High Yield» strategy, additional investments had to be taken into account, i.e., for the drip and overhead irrigation system (16,750 CHF/ha) and for the higher tree density (+9163 CHF/ha). For the «Organic» strategy, surcharges for the organic plant material (+7777 CHF/ha) were included.

3.4.3. Labor input

For the «PEP2018» strategy, a labor input of 643 h/ha was calculated. The labor input of the «PPP Reduced» and «High Yield» strategies was higher (5% and 33%, respectively), while the «Organic» strategy showed a 24% lower labor input (Table 4). The main labor input was required for harvesting (between 30 and 59% depending on the strategy), tree training (14–25%), manual pruning (12–23%), administration (5–8%), plant protection (including pest monitoring; 5–10%) and opening and closing of the nets (2–6%).

3.4.4. Yield fluctuations

Compared to the «PEP2018» strategy, the yield fluctuations were estimated to be higher for the «PPP Reduced» and «Organic» strategies and lower for the «High Yield» strategy.

3.5. Multi-criteria assessment

To facilitate the comparison of the investigated crop protection strategies, a multi-criteria assessment with the calculated indicators was performed. For each strategy, the results of each indicator were compared with the «PEP2018» reference strategy and the differences were classified according Table 2.

3.5.1. «PPP Reduced» strategy

Compared to the «PEP2018» strategy, the «PPP Reduced» strategy performed much better in terms of PPP use (Fig. 4), although both strategies are based on an integrated apple production system. While the «PPP Reduced» strategy achieved better performance regarding the

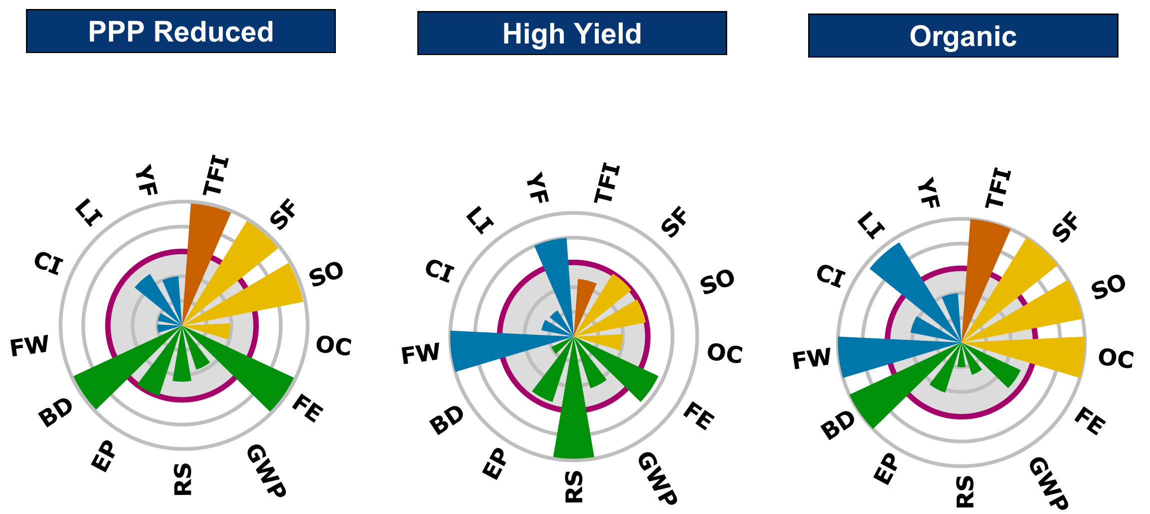

Fig. 4. Multi-criteria assessment: Performance of the investigated strategies («PPP Reduced», «High Yield», «Organic») compared to the reference strategy («PEP2018») for all 13 investigated indicators categorized in PPP use (brown), local ecotoxicological risks (SYNOPS: yellow), global environmental impacts (LCA: green) and economic impacts (full cost accounting: blue). Each circle represents a level of relative comparison with the «PEP2018» reference strategy, which is indicated as a pink circle. The grey area indicates that the performance of the strategy is worse than that of the reference strategy; the white area indicates a better performance. TFI: treatment frequency index; SF: risks to organisms of surface water; SO: risks to soil organisms; OC: risks to organisms of terrestrial off-crop-habitat; FE: freshwater ecotoxicity; GWP: global warming potential; RS: Resource use; EP: eutrophication potential; BD: terrestrial biodiversity; FW: farmer's hourly wage; CI: capital invested; LI: labor input; YF: yield fluctuations. «PEP2018»: average integrated strategy in 2018 based mainly on the use of synthetic PPP; «PPP Reduced»: integrated strategy with reduced PPP use and low residues but without yield losses; «High Yield»: conventional strategy with the aim of maximizing yields; «Organic»: average organic production in 2018. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ecotoxicological risks to organisms of surface waters and soils, it performed worse than the reference strategy in terms of risks to organisms of off-crops habitats. When comparing freshwater ecotoxicity and biodiversity as an impact assessment in LCA, the strategy «PPP Reduced» performed much better (caused significantly less ecotoxicity and had a positive impact on biodiversity) than the reference strategy «PEP2018». The effects on eutrophication potential and on resource use were similar for both strategies. However, a worse performance in terms of GWP was found compared to the reference strategy «PEP2018». Both the «PPP Reduced» and the «PEP2018» strategy performed similarly regarding the economic indicator labor input. However, the «PPP Reduced» strategy performed much worse in terms of farmer's hourly wage and invested capital. In terms of yield fluctuations, the «PPP Reduced» strategy was rated worse than the «PEP2018» reference strategy.

3.5.2. «High Yield» strategy

The «High Yield» strategy showed a slightly higher TFI compared to the «PEP2018» reference.

The local ecotoxicological risks calculated for organisms of surface waters and soils were similar between the two strategies, but the «High Yield» strategy had an impact on organisms of off-crop habitats. In terms of global environmental impacts, three indicators performed similarly for the «High Yield» and «PEP2018» reference strategies: freshwater ecotoxicity, GWP and the eutrophication potential. In terms of resource use, the «High Yield» strategy performed much better than the «PEP2018» strategy, but resulted in a much worse performance in terms of biodiversity. From an economic perspective, the «High Yield» strategy performed much better than the «PEP2018» reference strategy in terms of farmer's hourly wage and better regarding the expected yield fluctuations, but worse in terms of invested capital and labor input.

3.5.3. «Organic» strategy

The «Organic» strategy performed much better than the «PEP2018» reference strategy in terms of PPP use (Fig. 4), and also regarding the ecotoxicological risk to organisms of surface waters, soils and off-crop habitats. In terms of the global freshwater ecotoxicity, similar results were found compared to the «PEP2018» reference strategy. Although the «Organic» strategy performed significantly better in terms of biodiversity, it had much higher resource use and a slightly higher eutrophication potential and performed significantly worse in terms of GWP. From an economic perspective, the «Organic» strategy was much better regarding the labor input and farmer's hourly wage. Both the «Organic» strategy and the «PEP2018» reference strategy performed similarly in terms of invested capital, however, the «Organic» strategy was rated much worse regarding the yield fluctuations.

4. Discussion

4.1. Comparison of crop protection strategies

4.1.1. The «PPP Reduced» strategy

The better performance in PPP use compared to «PEP2018» was achieved by adopting various measures in the «PPP Reduced» strategy, such as the installation of a rain cover to reduce fungal diseases and by choosing a robust apple variety with a lower need for fungicide treatments. Additionally, the use of antagonists such as *A. pullulans* further minimised the amount of fungicides (including bactericides) in this strategy. Moreover, sulphur and potassium bicarbonate, which are approved for use in organic farming, were applied instead of treatments with synthetic fungicides in the second half of the season. In addition, the replacement of herbicides by mechanical weed control, the installation of an insect net to reduce the application of insecticides and the introduction of biological control measures such as pheromones and granuloviruses further reduced the use of PPPs in this strategy.

The better performance of «PPP Reduced» compared to «PEP2018» regarding local ecotoxicological risks resulted from a general reduction in the use of PPPs, and in particular by dispensing individual high-risk active ingredients such as chlorpyrifos-methyl. However, the replacement of pirimicarb, which poses a higher risk for surface waters organisms, with spirotetramat, which has been found to cause increased risks to beneficial organisms, had a negative impact on the risks to organisms in the off-crop habitats.

When comparing freshwater ecotoxicity as an impact assessment in LCA, the absence of copper in this strategy had a positive effect. Copper is persistent in the environment and can (depending on its bioavailability) cause high risks for aquatic organisms, but also for birds, mammals and soil macro-organisms (EFSA, 2018), and thus to be important in a long-term and global perspective. This strategy also had a better impact on biodiversity, as it promotes the accompanying flora in particular by dispensing with herbicides. As the assumptions for fertilization, yields and storage losses did not differ for both strategies, no difference in eutrophication potential, but a slight increase in resource use and even more in GWP was observed, caused by the adopted installation of an insect net, a rain cover and an irrigation system.

As yields and therefore the time required for harvesting were the same, both strategies did not differ much in terms of the economic indicator labor input. However, the additional installation of an insect net, a rain cover and a drip irrigation system almost doubled the invested capital and the depreciation of the invested capital. This led to higher annual costs exceeding even the revenue and ultimately resulted in a negative farmer's hourly wage. Moreover, the application of fewer and less effective PPPs can lead to higher annual yield fluctuations.

Although the «PPP Reduced» strategy delivered significant benefits in PPP use and risk reduction compared to the «PEP2018» reference strategy, accompanied by comparable or better performance on environmental indicators (except GWP), the unfavorable economic performance (in terms of farmer's hourly wage, invested capital, yield fluctuations) will hinder widespread implementation of this crop protection strategy. Economic incentives, such as higher prices or direct payments, would therefore be needed to make the «PPP Reduced» strategy more attractive. Farmers could be motivated to implement new crop protection strategies if peer-farms demonstrate how the use of PPPs can be successfully reduced (Bakker et al., 2021). However, more research is also needed to develop effective non-chemical plant protection.

4.1.2. The «High Yield» strategy

The slightly higher TFI of «High Yield» compared to «PEP2018» was a result of the higher frequency in fungicide, insecticide and herbicide application. Differences in local ecotoxicological risks for surface waters and soils were not found, mainly because the risk-dominant active ingredient chlorpyrifos-methyl was used in both strategies. However, the use of the active ingredient spinetoram, which poses an increased risk to beneficial organisms, had a negative impact on organisms of the off-crop habitats. The similar performance of the «PEP2018» and «High Yield» strategies in terms of local ecotoxicological risks could result from three reasons. Firstly, the current market demands high quality apples and the standard crop protection strategy «PEP2018» is already optimized to reduce yield and quality losses due to pests and diseases. Secondly, in Switzerland the choice of PPP is restricted by the PPP authorization and, thus, more effective and possibly more toxic PPP cannot be used in the conventional «High Yield» strategy. Third, the PEP guidelines (SAIO, 2018) currently contain few restrictions or incentives to reduce PPP use or avoid the use of high-risk substances in integrated production.

The freshwater ecotoxicity was marginally improved by a lower copper use per kg 1st class apples, the GWP and eutrophication potential were slightly increased because of irrigation. Since less land area is needed to produce 1 kg of 1st class apples, the resource use performance was better. However, this in turn led to a much worse performance in terms of biodiversity, as larger orchard areas are beneficial for biodiversity compared to the reference arable land. The strongly increased yields led to a significantly higher revenue from the sale of 1st class apples, which compensated for the additional investment for the irrigation system. The increase in labor input was linked to the increase in yields and thus, to the time that had to be spent on harvesting.

Conventional apple production systems underlying the strategy «High Yield» hardly exist in Switzerland at present, but could become economically attractive if the PEP guidelines were to become significantly stricter in the future. In terms of local ecotoxicological risks and environmental impacts, this would have only partially negative consequences (regarding the negative risks for off-crop habitats and for biodiversity) compared to the «PEP2018» strategy, and even a positive effect for resource use. However, this strategy would run counter to existing policy goals to further reduce the use and risks of PPPs.

4.1.3. The «Organic» strategy

Although fungicides (incl. bactericides) were applied equally frequently in both the «Organic» and the «PEP2018» strategy, the «Organic» strategy used fewer fungicides in tank mixtures and the bactericides were replaced by antagonists such as *A. pullulans* (against fire blight) resulting in a much lower TFI. In addition, the «Organic» strategy was based on the assumption that fewer insecticides would be used, pheromones and granuloviruses were used instead to protect against pests, and finally, herbicides were dispensed with altogether. As a result of the generally reduced PPP use, and because high-risk synthetic PPPs (such as chlorpyrifos-methyl or pirimicarb) were avoided, the ecotoxicological risk for the organisms of all habitats analyzed was significantly lower compared to «PEP2018».

The «Organic» strategy performed slightly worse regarding the LCA indicator freshwater ecotoxicity due to the higher copper use for the production of one kg 1st class apples. Since a larger area is needed to produce 1 kg of 1st class apples, this strategy had a positive impact on biodiversity. This is because the indicator takes also into account that apple orchards are more attractive habitats than arable land, which would be the most realistic alternative land use. In addition, the absence of herbicides also contributed to a higher in-crop biodiversity. However, the resource use was higher due to lower yields per hectare and additionally higher storage losses, resulting in higher demands for scarce land resources, but also due to the material and fossil fuels needed to produce 1 kg 1st class apples. The lower yields led ultimately also to a higher eutrophication potential per kg of 1st class apples, although the eutrophication potential per hectare is significantly lower using organic fertilizer. In addition, the use of organic fertilizer should also lead to a reduction in greenhouse gas emissions from the field. However, the main reasons for the poorer performance regarding GWP were again lower yields and higher storage losses, which led to a higher GWP of hail nets and machine use per kg 1st class apples, and the greenhouse gas emissions related to hot water treatment after harvest.

As no additional structures were required for either strategies, almost no differences were found in the economic indicator of invested capital. The fact that lower yields required fewer working hours for harvesting had a positive effect on labor input, and the premium price paid for organic apples resulted in a much better performance of the farmer's hourly wage despite the lower harvest. However, in years with unfavorable conditions (e.g., weather, pest pressure, etc.) there are only few compensatory measures available to maintain yields and thus, the «Organic» strategy performed worse regarding the yield fluctuations.

The «Organic» strategy showed clear benefits for the reduction of PPP use as well as its ecotoxicological risks and performed also favorable in terms of biodiversity. Thus, this strategy could contribute to the political goals to reduce PPP use and risks. However, the lower yields and higher storage losses led to an increase in other environmental impacts per kg 1st class apples (resource use, eutrophication potential, GWP) and thus, conflict with other policy objectives. From an economic point of view, the «Organic» strategy showed advantages, but was associated with higher production risks (yield fluctuations). Although the «Organic» strategy has a long tradition in Switzerland, only 11% of the total apple area was managed organically in 2019. However, a strong increase of 30% of organic apple area was observed between 2017 and 2019 (Federal statistical office, 2021). A further increase in the production of organic apples would only be possible with an increased demand for these apples, as the «Organic» strategy is only profitable due to the additional price premium. Furthermore, Home et al. (2019) showed that while organic farming is economically beneficial in Switzerland, social factors (such as neighbors or family members with negative attitudes towards organic farming), lacking awareness and trust in alternative plant protection measures and logistic factors (e.g. longer travel distance to product delivery points) are high barriers for more farmers to switch to organic farming.

4.2. Most influential parameters and sensitivity analyses

For most indicators, results were determined by only a few parameters. In the following, the most influential parameters for each indicator and possible leverage effects for improving the crop protection strategies are discussed. The robustness of the results is explained using various sensitivity analyses.

4.2.1. PPP use

As indicator of PPP use the TFI was chosen, which is a commonly used indicator of PPP intensity (Simon et al., 2011), as it takes into account both the number of applications and the dosage applied relative to an *approved* standard dose. The recommended dose of PPP varies greatly in apple orchards for different seasons related to the leaf volume of the trees, the seasonal risk of sunburn (e.g., in case of too high sulphur dosage), or the target organisms. For this reason, the standard dose approved in Switzerland is given as a range for many PPPs. In a sensitivity analysis, the TFI was calculated not only on the basis of the maximum approved dosages, but additionally on the basis of the median and the minimum approved dosages. The ranking of the strategies in terms of TFI was not changed, but the TFI increased for all strategies, especially in the «Organic» strategy (SI Fig. S2).

Fungicides are generally the most frequently applied PPP in apple orchards. One way to reduce the use of fungicides is to grow robust apple varieties (Simon et al., 2011). Especially for organic farming, the use of a robust variety is recommended. The most popular and most frequently grown variety in Switzerland, however, is the scab-susceptible "Gala", which had a TFI of 22.1 in the reference strategy and a TFI of 11.9 in the «Organic» strategy with respect to the use of fungicides. In a sensitivity analysis, the effect of choosing a robust variety "Bonita" for the «Organic» strategy was tested and resulted in a TFI of 7.5 for fungicides (SI Fig. S1). Even when growing a robust variety, fungicide-free production is not possible without changes in yield, quality or post-harvest losses, as some treatments are still needed to maintain resistance of the cultivar against scab and to treat other diseases such as powdery mildew or fire blight. Fully resistant cultivars against multiple pests (e.g. scab, mildew, fire blight) are not yet available. With a robust variety, the «Organic» strategy had an overall TFI (including insecticides) of 9.8, which is equal to that of the «PPP Reduced» strategy. The results of our analysis indicate, that robust varieties are a solution to reduce the use of fungicides in apple orchards without major trade-offs for other analyzed indicators (see below). However, Nuijten et al. (2018) showed that the introduction of new robust apple varieties into European markets is challenging due to lock-ins. Changes can only be achieved if all actors in the trade chain (farmers, retailers, consumers) adapt to the changes at the same time. The authors concluded that demand must be actively created (pull-effect) and good cooperation must be established in the retail chain.

Other ways to reduce fungicide use can be achieved by installing a rain cover or a post-harvest hot-water treatment to reduce storage losses. However, both measures showed disadvantages for some environmental indicators and the rain cover had additional disadvantages for economic indicators while post-harvest treatments resulted in additional costs (0.15 CHF/kg apples). Biological control by antagonists (e.g. *A. pullans*) can reduce the use of bactericides, but in the case of scab and powdery mildew, biological control agents cannot completely replace synthetic PPPs as they tend to reduce but not control diseases (Shuttleworth, 2021). In addition, monitoring and forecasting tools (e.g. www.agrometeo.ch) can optimize spray scheduling and thus reduce fungicide use (Shuttleworth, 2021). However, at present, a completely fungicide-free strategy does not seem possible without lowering the high quality demands of trade and consumers.

A herbicide-free production was assumed in the «PPP Reduced» and «Organic» strategies, but resulted in an 18% higher GWP from the process crop protection (i.e. when comparing «PPP Reduced» to «PEP2018»). Insecticide-free production was not assumed in any scenario, but a strong reduction could be achieved with applications of pheromones and granuloviruses, and an installation of an insect net. However, the latter showed negative side effects in terms of GWP. Other ways to reduce PPP use have not been considered in this study. Simon et al. (2010) emphasized the important role of biodiversity in regulating pest species in orchards, for example by maintaining food webs within the agroecosystem. This was also demonstrated by García et al. (2021), who showed that installing nest boxes for insectivorous birds in orchards halved the biomass of tree-dwelling arthropods and reduced the incidence of apple pests.

Finally, the use of PPPs can be substantially reduced through a combination of methods (cultivation of resistant/robust varieties, use of insect nets and rain covers, use of pheromones, mechanical weed control and other alternative methods) (Ackermann et al., 2021). In addition, advanced precision spraying techniques could help to significantly minimize application rates and avoid emissions to off-field habitats (Mahmud et al., 2021).

4.2.2. Local ecotoxicological risks

Single active ingredients usually dominated the local ecotoxicological risks. The choice of active ingredients is therefore critical. In this study, we have adopted a typical and realistic crop protection strategy with the most commonly used active ingredients. To test the robustness of results, various sensitivity analyses were carried out.

Chlorpyrifos-methyl, for example, was the highest or second highest risk active ingredient in the «PEP2018» and «High Yield» strategies in surface waters, soil and off-crop habitat. As the authorisation of this substance was withdrawn in summer 2019, a sensitivity analysis was carried out by replacing chlorpyrifos-methyl with acetamiprid in the «PEP2018» reference strategy. This resulted in a 76% and 91% lower risk for the «PEP2018» strategy in surface waters and soils, respectively, but to a 21% higher risk in off-crop habitats, because compared to chlorpyrifos-methyl, acetamiprid showed lower risk to surface waters and soils but higher risks to off-crop habitat. Still, «PPP Reduced» and «Organic» showed significantly lower risks than the «PEP2018» strategy with acetamiprid instead of chlorpyrifos-methyl for surface waters and soils, but the «High Yield» strategy showed higher risks compared to the «PEP2018» strategy with acetamiprid for all three compartments (SI Fig. S5).

When captan was replaced by the equally commonly used active ingredient folpet in the «PEP2018» strategy analysis, the risks for all compartments remained very similar (SI Fig. S5). To reflect years with high pest pressure, a doubling of the number of fungicide applications was assumed in the «Organic» strategy. This doubling resulted in a 26–140% higher risk in the different environmental compartments, but these were still significantly lower compared to the «PEP2018» strategy. Assuming that the robust variety "Bonita" would be grown in the «Organic» strategy, the risks in the three compartments were between 6 and 38% lower than for the scab-susceptible variety (SI Fig. S5).

Overall, replacing single active ingredients had a strong influence on the ecotoxicological risks of individual strategies, but compared to the «PEP2018» and «High Yield» strategies, the risks of the «Organic» and «PPP Reduced» strategies were always fundamentally lower for surface water and soil and for the «Organic» strategy also for off-crop habitat.

In this study, an average pest and disease pressure was assumed for all crop protection strategies. In reality, this can vary considerably from year to year or from production region to production region, and therefore the use of active ingredients and the associated risks can also vary. In addition, for most pests and diseases, farmers can choose between several PPPs with different active ingredients to protect crops. In this study, only a limited number of scenarios could be evaluated. To better represent the variability of risks within each crop protection strategy, spray records of famers covering the different crop protection strategies would be needed. However, only few spray records are available for research (not only in Switzerland). In our study, data of the AEI farm network (de Baan et al., 2015) were used to create a spray sequence for the «PEP2018» reference strategy, but adjustments were made for all other strategies together with experts, as spray records were missing for these strategies. In future, professional users of PPPs in Switzerland could be obliged to record their PPP use in a federal information system (Bundesblatt, 2021). This would allow a better understanding of the variability of risks within different apple production systems.

Our results show that substituting high-risk PPPs with low-risk PPPs (so-called «chemical substitution») or non-chemical alternatives are an effective method to reduce risks for the environment. However, farmers and policy-makers need adequate information on the risk potential of active ingredients and on the availability of chemical or non-chemical alternatives. When classifying the risks of active ingredients, both the different environmental compartments and human health should be considered to avoid risk shifting. In addition, resistance management must be ensured. Steingrímsdóttir et al. (2018) and Korkaric et al. (2020) give examples of how active ingredients can be compared and ranked according to their risks and assess where a substitution of high risk PPP would currently be possible.

4.2.3. Global environmental impact

Yield and storage losses had a strong influence on the global environmental impact, as the indicators were calculated per kg $apple_{1st}$. Consequently, a higher yield and lower storage loss had positive effects on the indicators, with the exception of biodiversity. As the «PPP Reduced» strategy had higher yields compared to the «Organic» strategy, the former showed better environmental performance. In addition, the yield-optimized «High Yield» strategy performed better than the «PEP2018» reference strategy in terms of resource use. Increasing yields could therefore be a measure to reduce environmental impact per kg of apples, especially in organic farming. In the last three decades, apple yields in Switzerland have already increased by 30% (Schweizer Obstverband, 2020), so that a further increase in yields could be a challenge. Furthermore, intensification carries the risk of negative side-effects within a production region. For example, increased nitrogen inputs can generally lead to increased nitrogen leaching into surface and groundwater, biodiversity loss and higher emissions of nitrous oxide, a very potent greenhouse gas (Röös et al., 2018).

The environmental impacts were additionally calculated per hectare instead of per kg $apple_{1st}$, as recommended by van der Werf et al. (2020). Here, the «Organic» strategy clearly showed the lowest and the «High Yield» strategy the highest environmental impacts of all strategies for all indicators except for freshwater ecotoxicity, where the «PPP Reduced» strategy showed the lowest impact (SI Fig. S6). Similar trends were found in a study in France comparing scab-prone organic apples with conventional apples based on the same two functional units 1 kg apple and 1 ha (Alaphilippe et al., 2013). The impact per ha was lower for the organically grown apples compared to conventionally grown apples for non-renewable energy use and eutrophication and similar in terms of GWP, while the impact per kg of organically grown apples compared to conventionally grown apples was higher for non-renewable energy and GWP and similar for eutrophication. However, the choice of the functional unit did not change the results for four additional indicators analyzed in the French study. The organic strategy performed better in terms of human toxicity and ecotoxicity and the conventional strategy performed better in terms of ozone formation and acidification, regardless of the functional unit chosen (Alaphilippe et al., 2013).

While for resource use and GWP the impacts are of global importance and should therefore be considered per unit of product, the impacts of eutrophication and ecotoxicity are relevant at both local and global scale. Detailed assessments of local ecotoxicological risks, such as those carried out in our study, provide additional relevant information on the stress on aquatic or terrestrial ecosystems in the apple-growing regions. For a more comprehensive view of the environmental impacts of different crop protection strategies, a local assessment of eutrophication or ecosystem services provided by the apple orchard could be added (see e.g., Demestihas et al., 2019).

The assumed amount of copper to be applied per strategy was the main cause of the level of global freshwater ecotoxicity. Copper is persistent and its toxic effects on numerous aquatic flora and fauna has been studied intensely (EFSA, 2018). Thus, copper is of high importance for a long-term global assessment of chemicals. However, it is a challenge to assess metallic and organic substances with the same assessment method in LCA. Therefore, Fantke et al. (2018) propose to assess the effects of organic and metallic substances separately. When the pesticide copper is not taken into account, the «Organic» and «PPP Reduced» strategies both performed better than the «PEP2018» reference strategy (51% and 52% lower freshwater ecotoxicity, respectively), as fewer organic chemicals were generally assumed to be applied, while the «High Yield» strategy still performed similarly compared to the «PEP2018» reference strategy (−10%). Thus, without considering copper, the results were similar to those for local ecotoxicological risks for surface waters.

For biodiversity, the most important factor determining the differences between the scenarios was the land used to produce one kg $apple_{1st}$, with higher land use having a positive effect on biodiversity, as the alternative land use (arable crop land) had a lower diversity than apple orchards. Furthermore, the definition of the reference land use had a strong influence on all results. If the biodiversity value of each strategy were compared to an area with maximal biodiversity (i.e. a species-rich grassland with a biodiversity score of 21.3) instead of an average agricultural land use (biodiversity score of 7.6), then all apple production systems would have a lower biodiversity and thus a negative impact on biodiversity (SI Table S16). Here, the «High yield» strategy would perform best (+33% compared to the «PEP2018» reference strategy) with the lowest land requirements for the production of 1 kg of $apples_{1st}$, while the «Organic» strategy would perform worst (−53% compared to the «PEP2018» reference strategy). In this study, the SALCA biodiversity model was tested for the first time in a case study on low-stem apple production (Van der Meer et al., 2017). It proved to have little sensitivity to PPP use, as the negative impacts of the PPP applications within all strategies are assessed without considering the toxicity of the single substances. The greatest differences between the strategies were found for the arable and grassland flora and the birds in the inter-row and orchard habitats, mainly caused by the avoidance of herbicides, less intensive use of mineral fertilizers, less inter-row cuttings and the establishment of hedges or flower strips.

For global warming potential, resource use and eutrophication, the fossil fuel-powered machinery accounted for a relevant share of the impacts, and switching to a more environmentally friendly fuel source could reduce impacts in all three categories. The assumed 6-month storage in all strategies and the post-harvest hot water treatment in the «Organic» strategy also made relevant contributions to the global warming potential, resource use and eutrophication potential. In addition, packaging of apples and transport to consumers, which were not considered in this study, can cause relevant additional environmental impacts (Longo et al., 2017). Improving these post-harvest processes would therefore also help to reduce the overall environmental impact of apples.

4.2.4. Economic impact

The price of 1st class apples had a high impact on farmer's hourly wage, while direct payments had only a low effect (as also shown by Mouron and Carint, 2001) and may not provide the necessary incentives to switch to a more environmentally friendly strategy in apple production. Establishing a market that pays higher prices for 1st class apples grown with the «PPP Reduced» strategy seems more promising. A 33% higher price for 1st class apples grown with the «PPP Reduced» strategy would lead to the same farmer's hourly wage as with the «PEP2018» reference strategy, a 55% higher price (an amount between prices paid for conventionally and organically grown apple) would lead to a 112% higher hourly wage compared to the «PEP2018» strategy. In terms of societal pressure to reduce PPP use and risks, increased demand for apples produced with lower ecotoxicological risks and global environmental impacts seems possible. In an experiment conducted by Marette et al. (2012), French consumers were willing to pay a 14% higher price for apples labelled "Few pesticides" compared to conventional apples, and a 39% lower price compared to organic apples. However, Möhring et al. (2020) pointed out that consumers expect a pesticide-free production and communicating a "reduced pesticide use" on food products would be challenging. Being able to sell pesticide-free apples in the supermarkets seems unrealistic at present, unless expectations for low prices, shelf life and fruit quality are drastically lowered and, for example, purely aesthetic fruit damages are accepted.

As there is currently no market in Switzerland for apples grown according to the «High Yield» strategy, the price assumptions were uncertain. For «High Yield», a 12% lower price for 1st class apples would lead to a comparable farmer's hourly wage as in the «PEP2018» strategy, with a 23% lower price the farmer's hourly wage would be 0 CHF/ha. This illustrates the strong influence of the selling price on farmer's hourly wage in each strategy and the role consumers can play in changing apple production systems.

Even with the «PEP2018» strategy, the farmer's hourly wage was below the minimum wage of 22 CHF/h recommended by the Swiss Trade Union, which could only be achieved with an 8% higher price for apples produced according to «PEP2018».

In the «PPP Reduced» strategy, the assumed installation of a rain cover and the therefore necessary irrigation system required more invested capital. Even if apple prices were higher in the «PPP Reduced» strategy, which could help to recoup this investment, the high initial capital requirement could still be a major obstacle for many farmers to implement this crop protection strategy.

For the «PEP2018» reference strategy it was assumed that a hail net is installed, but that no irrigation system is in place. However, irrigation systems are already common in drier apple production regions in the southwest of Switzerland. For these farms, the economic assessment would be different.

The time required for harvesting, but also for pruning and tree training was decisive for the labor input; the time required for plant protection was significantly lower in all scenarios. The increased labor input for mechanical weed control and for opening and closing nets was not very relevant in this overall assessment. The additional effort for non-chemical plant protection thus does not seem to be a major obstacle for the implementation of such strategies.

For yield fluctuations, the availability and effectiveness of crop protection measures in years with high pest or damage pressure was important. Here, the «Organic» strategy had fewer plant protection options compared to the «PEP2018» or «High Yield» strategies. In addition, not using chemical thinning (as assumed in the «Organic» strategy) can lead to greater yield fluctuations. The expected stronger yield fluctuations in the «PPP reduced» and «Organic» strategies could be an additional obstacle to the implementation of these strategies (Mzoughi, 2011), especially for risk-averse farmers.

4.2.5. Applicability of the methods used and the achieved results

In this study, four exemplary crop protection strategies were defined, representing an average production year. However, spray sequences and cultivation parameters such as yields show a strong temporal as well as spatial variation. In individual years, weather events can have a strong influence on the occurrence of diseases and pests (Hirschi et al., 2012) as well as on yields (Dalhaus et al., 2020). Prices depend on markets, which also have strong temporal dynamics and vary from country to country.

Inter-annual variations in yields were taken into account in the assessment of environmental and economic impacts. For the corresponding indicators, different years with low, average or high yields were modeled to obtain an average assessment.

The use of PPPs and their ecotoxicological risks may vary depending on pest and disease pressure and the apple variety grown. The sensitivity analysis showed that the ranking of strategies did not change with different assumptions on the PPP used. In years with high pressure of pests or diseases, the TFI would increase for all strategies due to more frequent treatments. As a rule, the same active ingredients are applied more frequently when damage or pest pressure is higher. Thus, as long as no ingredients with higher risks are used, risks will not necessarily increase either.

The methods applied in this study to evaluate trade-offs in apple production can be applied in other apple studies in other countries, as well as for other crops. However, the results of our study represent the specific situation in Switzerland and cannot be generalized one-to-one to another country or crop. The most influential parameters identified above, such as yields, prices, but also labor costs, approved PPP, incidence and type of pests and damage, general cultivation practices (installation of hail nets and irrigation systems), are likely to be also relevant in other production systems. However, depending on the actual context and production system, the conclusions might be different.

4.3. Trade-offs and synergies between indicators

Based on our analysis with 13 indicators, significant trade-offs could be identified. Some of these trade-offs are inherent to the way indicators were calculated. There is a trade-off between biodiversity and resource use assessed per kg apple$_{1st}$, where the first increases with increasing land use and the second decreases. However, this only applies to the specific case of apple production in Switzerland, where apple orchards have a higher biodiversity than the reference area (arable crops). In countries where natural habitats with high biodiversity are converted into apple orchards, this ratio could be exactly reversed. Labor input was strongly dominated by harvesting, so increasing yields (to reduce greenhouse gas emissions) would also increase labor input. It was also assumed that a reduction in PPP use would lead to greater yield fluctuations, as non-chemical crop protection is not as effective as chemical crop protection and thinning (with plant growth regulators) in all years.

For other indicators, there were trade-offs that could possibly be resolved by improving the processes. For example, the installation of a rain cover led to a strong reduction in fungicides used, but also to higher greenhouse gas emissions and invested capital, as well as lower farmer's hourly wage. Increasing the price of apples grown with the «PPP Reduced» strategy could increase farmer's hourly wage, and switching to non-fossil fuels (e.g. using an electrical lifting platform) could reduce greenhouse gas emissions from the machines when opening and closing the insect and hail net. Rain cover with a reduced greenhouse gas emissions are currently being developed. Another example for a trade-off is the assumed mechanical weed control to avoid herbicides, which led to higher greenhouse gas emissions. Here, too, a switch to other fuels could reduce emissions, but such electric machinery first needs to be developed. With the «Organic» strategy, lower PPP use and lower risks as well as a higher farmer's hourly wage could be achieved, but resource use and greenhouse gas emissions per kg of apple were increased.

The study also showed synergies between the indicators. The «PPP Reduced» strategy resulted in lower PPP use, lower risks to surface waters and soils, lower global freshwater ecotoxicity and higher biodiversity, with no impact on consistently high yields and storage losses. With the «Organic» strategy, PPP use and risks could be significantly reduced and biodiversity increased, while at the same time farmer's hourly wage could be increased and the labor input reduced.

5. Conclusions

The results of this study show that a reduction of PPP use and ecotoxicological risks in apple orchard systems is not possible without environmental or economic compromises. None of the strategies performed better on all the 13 assessed indicators. As expected the «Organic» and «PPP Reduced» strategies showed lower PPP use and ecotoxicological risks. However, the «Organic» strategy showed higher environmental impacts per kg $apple_{1st}$ for most indicators mainly due to lower yields, and the «PPP Reduced» strategy had an increased global warming potential due to emissions related to the rain cover and insect net. The «Organic» and «High yield» strategies showed the highest farmer's hourly wage. In the «PPP Reduced» strategy the increased capital requirement for the rain cover and insect net without a price premium for 1^{st} class apples lead to a negative farmer's hourly wage.

This study analyzed the most important factors for each indicator and can serve as a starting point for further improving crop protection strategies for apples in terms of PPP use, local ecotoxicological risks, global environmental impacts and economic performance. In the future, social indicators (e.g. the impacts on human health of farmers and consumers or the evenness of workload distribution (e.g., Pelzer et al., 2012)) should be included in the assessment of crop protection strategies to also provide information on trade-offs in the third pillar of sustainability.

To reduce PPP use and ecotoxicological risks without major trade-offs, joint efforts by farmers, trade and consumers are required, e.g., the introduction of robust varieties, the acceptance of purely “cosmetic” fruit damage, the reduction of storage time and losses through more seasonal apple consumption, or the economic rewarding of the effort required for the implementation of alternative crop protection strategies. This analysis of PPP use and risks as well as the environmental and economic impacts of crop protection strategies based on 13 quantitative indicators provides a valuable information basis for identifying and designing more sustainable apple plant protection strategies.

CRediT authorship contribution statement

L.B. and O.D. designed and directed the project, M.M. defined the strategies with the help of experts, calculated all indicators and analyzed the results with the support of T.N. (LCA), E.B. (economics), P.J. (biodiversity), L.B. (ecotoxicity) and J.F.B. (preparation of figures). L.B. and J.F.B. wrote the article with contributions from M.M. and O.D. and all authors gave critical feedback on the manuscript.

Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2022.03.008.

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