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Sustainability Assessment of Plant Protection Strategies in Swiss Winter Wheat and Potato Production

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Abstract: Production of arable crops in Switzerland is subsidized for services performed within the Proof of Ecological Performance (PEP) program, the crop protection part of which is based on IPM principles. Within PEP, chemical insect control must rely on those approved insecticides that are deemed harmless for beneficial arthropods. Approved insecticides potentially impacting beneficial arthropods may also be applied, but only if unavoidable and with an official permit. In order to assess the ecological and economic sustainability of this PEP program, a reference insecticide strategy illustrating the current PEP requirements was compared with other strategies. For this purpose, a sustainability assessment taking account of ecotoxicological risks and economic viability in addition to the preservation of beneficial arthropods was performed according to the SustainOS methodology. The results show that the one-off use of *Audienz* (spinosad) to control cereal leaf beetle (*Oulema melanopus*)—a key pest in winter wheat—would significantly improve sustainability vis-à-vis the reference (*Nomolt* (teflubenzuron) plus *Biscaya* (thiacloprid)). However, in the case of the Colorado potato beetle (*Leptinotarsa decemlineata*), in potato crops, where *Audienz* is considered the reference, no alternative would exhibit better sustainability. Moreover, the study shows that strategies using *Novodor* (*Bacillus thuringiensis*) protect beneficial species well but have the drawbacks of increased yield risk and higher costs. The conclusions drawn from these analyses allow recommendations for modifications of the PEP requirements for these two pest insects. The SustainOS methodology, a multi-step process combining expert knowledge with quantitative assessments including a sensitivity analysis of key target parameters and a rule-based aggregation of assessment results, yielded valuable insights into the sustainability of different crop protection strategies.

Keywords: sustainable agriculture; plant protection strategies; winter wheat; potato; full cost calculation; ecological risk assessment; *Oulema melanopus*; *Leptinotarsa decemlineata*

1. Introduction

Integrated Pest Management (IPM) is widely accepted as a holistic crop protection approach that aims to create resilient and sustainable agro-ecosystems [1]. Recently, the European Union established a Framework Directive on the Sustainable Use of Pesticides that included a definition of IPM, based on eight principles (Directive 2009/128/EC); moreover, member states are in the process of establishing national IPM programs [2]. In Switzerland, IPM was introduced as part of Integrated

Production in the years between 1970 and 1980 [3]. Since then, it has gained recognition and become the mainstream production scheme, supported by the national subsidy program established under the Direct Payment Ordinance of the Swiss Law on Agriculture [4]. At present, approximately 85% of the usable agricultural area is managed according to Integrated Production requirements, as compared to the 12% farmed according to the Organic Production Program [5]. For winter wheat, half of the IPM area in Switzerland falls under the Swiss Extenso Program, which forbids the application of any insecticides and fungicides. Although it is recognized that the implementation of IPM depends strongly on the motivation of farmers, other important elements of most IPM certification schemes have been identified as the availability of qualified advisors, continuous training and education, precise guidelines, checklists, and evaluation schemes [6,7]. The requirements for subsidies in Switzerland are described in detail in the Proof of Ecological Performance (PEP) [8].

Most recent descriptions of the IPM principles [1,6] include the caveat that pesticides should only be used when preventive or non-chemical direct measures do not provide sufficient crop protection, and crop damage or losses would consequently surpass economic damage thresholds. If their use is unavoidable, pesticides should be as selective as possible for the target species, and should minimize the side-effects on non-target organisms, in particular on arthropod natural enemies involved in pest regulation. Several sources provide comparative information on the impact of various insecticide active ingredients on non-target arthropods [9,10]. Among these sources are also websites of producers of beneficial organisms such as Biobest [11]. Based on such information, it is possible to classify approved insecticides in terms of their impact on key beneficial species in particular crops, such as winter wheat and potatoes in the present study [12].

In accordance with the abovementioned IPM principles, the restrictive use of pesticides is part of the Swiss PEP. In Switzerland arable crops cover 403,653 ha (38%) of the usable agricultural area [5], and within this acreage, winter wheat (80,000 ha) and potatoes (11,000 ha) are among the most important crops. The PEP guidelines restrict the use of insecticides in these crops.

If damage thresholds (*i.e.*, the point where economic loss due to pest impact on yield becomes higher than treatment costs) are exceeded, farmers may make unrestricted use of a number of insecticides, characterized by a narrow range of efficacy, which target key pests. The cereal leaf beetle (*Oulema melanopus*) is considered a key pest in winter wheat. It has been demonstrated [13] that a density of one larva per stem results in average yield losses of 5.4%, confirming similar results from Germany [14] and calculated as an economic damage threshold of 0.6–1.4 larvae per stem, depending on several parameters (e.g., variety). The Colorado potato beetle (*Leptinotarsa decemlineata*) and potato aphids (*Aphis* spp., *Macrosiphum euphorbiae*, and *Myzus persicae*) are key pests in table potatoes [9,15]. The damage threshold applied for the Colorado potato beetle in Switzerland is based on a series of experiments showing that a yield potential of 400 dt/ha will be reduced on average by 0.6% per larva feeding on one plant [15]. While the Colorado potato beetle is the only major pest in many countries, in Switzerland potato aphids can also cause economic damage in table potatoes by causing plant leaves to perish earlier, thereby shortening the ripening period of tubers [16]. Although approved for use in Switzerland, broad-spectrum insecticides that could interfere with the regulatory effect of beneficial arthropods may not be applied under PEP. However, if, based on their pest monitoring, farmers can prove that infestation pressure is above the threshold, they may request a permit, issued by a cantonal plant protection advisory service, to use approved broad-spectrum insecticides, given that the mode of action of some of those (e.g., neonicotinoids, pyrethroids) provides a high control efficacy. As yet, experimental data verifying thresholds for insecticide treatments and justifying broad-spectrum insecticide applications are scarce, in particular because the economic impact of crop losses may vary according to current market prices, variety, and farm-specific parameters such as machinery. On the other hand, although the key beneficial arthropods in these crops are known, little is known about their potential for controlling the key pests of winter wheat and potatoes in Swiss agriculture [12]. Therefore, to define the 2014–2017 Agricultural Policy, the Swiss Federal Office for Agriculture (FOAG) aims to test, and if necessary adapt, the relevant PEP requirements. The FOAG tasked Agroscope with carrying out the study described in this paper.

In this study, we applied SustainOS [17], a sustainability assessment concept relying on an expert group, to compare the currently implemented PEP restrictions in insecticide use in winter wheat and table potatoes with alternative management scenarios. In particular, the methodology assesses the potential impact of each scenario on environmental and economical sustainability. While Swiss PEP requirements vis-à-vis non-target arthropods focus on pest antagonists (beneficial arthropods) only, the SustainOS dimension for ecological sustainability is broader, taking into account terrestrial and aquatic risks in addition to an indicator of the preservation of beneficial arthropods. The specific aim of this study was to provide additional criteria for the decision on acceptable pesticide application strategies for winter wheat and potatoes. By applying SustainOS to an agricultural context that currently lacks evidence-based scientific data, we expected (i) to elucidate how the compared pest control scenarios may impact winter wheat and potato production in Switzerland; and (ii) to gain a better general understanding of the overall sustainability of crop protection strategies, as implemented under the Swiss PEP, which defines a system of special permits for broad-spectrum insecticides that could interfere with the regulatory effect of beneficial arthropods.

2. Materials and Methods

2.1. Sustainability Assessment Procedure

The sustainability assessment was conducted according to the "SustainOS" approach. This methodology was developed between 2008 and 2010 as part of the EU Project ENDURE for the comparison of plant protection strategies in fruit production, and tested in five European countries [18–20]. SustainOS is an expert-based approach in combination with quantitative assessment methods. The scheme was originally developed for apple production systems but can be applied to all kinds of perennial and arable cropping systems. It includes five elements (Figure 1a–e). These five elements must be defined by an expert group (see next section) representing the relevant competences for a given study goal. As step (a), the expert group defines context and target parameters as a frame in which different crop protection strategies will subsequently be defined (Figure 1a). As step (b), the expert group selects quantitative assessment methods (Figure 1b) in order to address the objectives of the study, in our case the preservation of beneficial arthropods, minimizing aquatic and terrestrial risk of pesticides, and maintaining economic viability of the farm, respectively. Step (c): The various output variables of the assessments build the "basic attributes" at the bottom of the hierarchical attribute tree (Figure 1c, attributes in grey). In step (d), the quantitative results are transformed into qualitative ratings in order to aggregate them into attributes of higher levels (Figure 1d). As step (e), the rating results are synthesized for the main dimensions of sustainability, which in our case are ecology and economics (Figure 1e). These five steps will be described further in the following sections.

2.2. Selection and Working Procedure of the Expert Group

The expert group was selected with a view to covering all the competences required to define crop protection strategies and conduct the sustainability assessment. It includes researchers, advisory-service agents, farmers, and Federal Office of Agriculture employees (Table 1).

The expert group held three working sessions: the first to define context and target parameters, the second to define current and alternative crop protection strategies, and the third to discuss and interpret assessment results.

Parameter definitions were proposed and justified by the respective experts based on their background information such as statistical data, the literature, and personal experience. Parameter definitions and values were discussed in the group until consensus was reached. In the chosen working process, experts provided their input on parameters without access to the subsequent assessment process. The idea that the group deliberately biased parameters based on hidden agendas can therefore largely be ruled out.

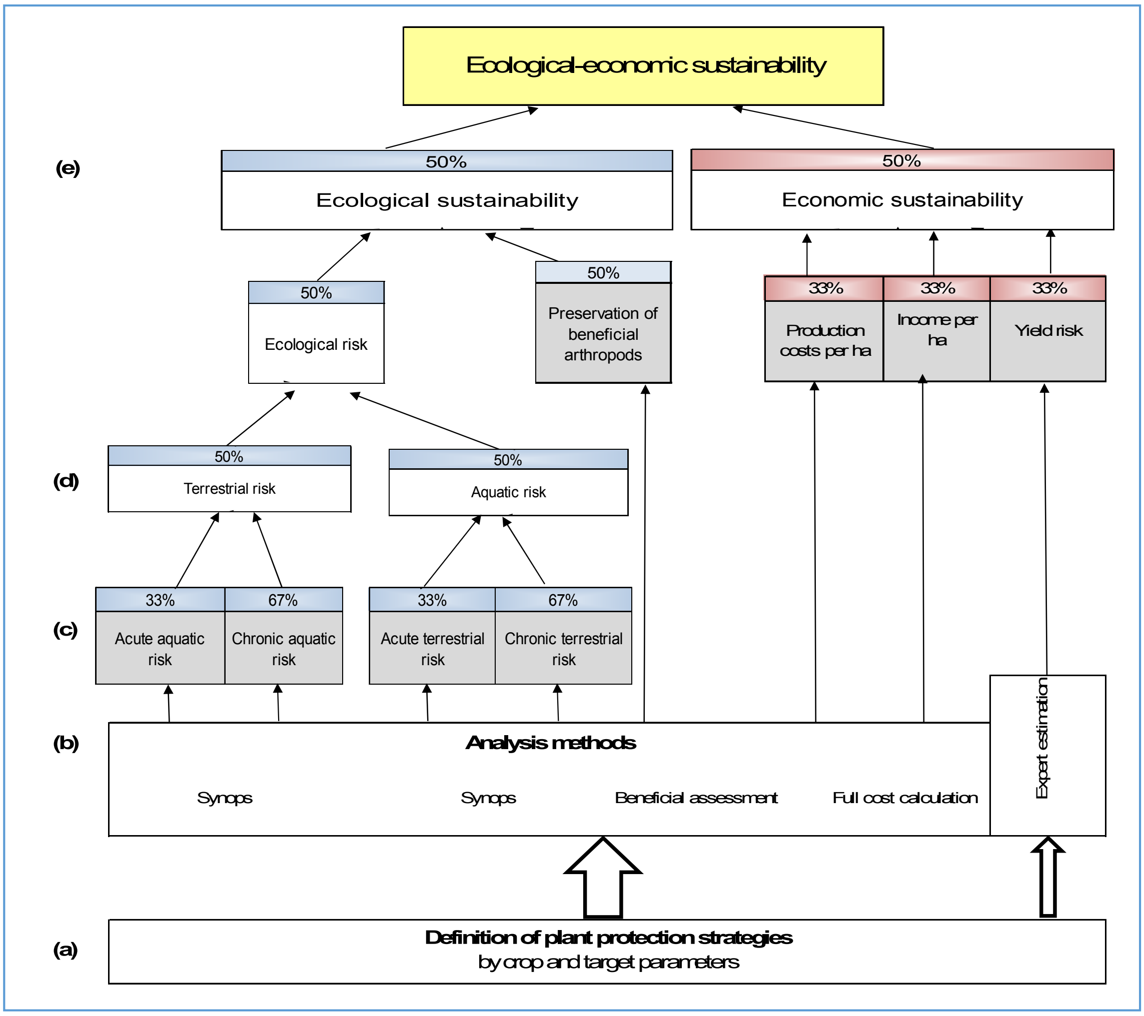

Figure 1. Five-step scheme (**a**–**e**) of sustainability assessment for plant protection strategies in winter wheat and table potato production (Adapted from [18]).

2.3. Definition of Context and Target Parameters

Realistic crop protection strategies can only be defined and assessed if assumptions for agronomic context parameters and production targets are fixed. Context parameters include geographic region, plant cultivar, plant density, damage threshold level of the pests under study, pressure of fungal diseases and weeds, drift reduction techniques, soil management, fertilizer inputs, and price of farm product (Table 2). According to the aim of this study, the assessment assumes that the damage thresholds for the cereal leaf beetle in winter wheat production and for the Colorado potato beetle and aphids in potato production have been exceeded. Further context parameters such as distance to water and drift reduction techniques influence the terrestrial and aquatic impacts of pesticide applications.

Target parameters define the expected yield potential and efficacy of crop protection strategies, as well as the extent to which degree resistance management should be taken into account (Table 2). The definition of yield potential was set in line with assumptions for fertilizer input. The efficacy of crop protection strategies is a key parameter of economic success. Table 2 provides an overview of context and target parameters defined by the expert group as representative of Swiss good agricultural practice. The values refer to a model plot of one hectare and one year.

Table 1. Competences represented by the expert group.

Experts (Number)	Competences
Researchers (6)	• 2 specialists for sustainability assessment with experience in applying SustainOS methodology, responsible for the working process • 2 entomologists with expert knowledge on wheat and potato pests and beneficial organisms • 1 specialist in pesticide risk analysis using the SYNOPS model • 1 economist specializing in full-cost calculation for agricultural production
Advisory service agents (3)	• Implementation of PEP directives at farm level, including knowledge about the frequency of issue of special permits for the application of pesticides whose use is restricted under PEP • Providing an overall view of regional crop management practices, pest and disease pressure
Farmers (3)	• Practice in winter wheat and potato growing, in the main production regions of Switzerland • Represent farmers association of Swiss wheat and potato growers • Experience of the feasibility of crop management strategies from the farmer's perspective
Federal Office of Agriculture (2)	• Swiss legacy for sustainable agriculture • Defining the principles of the PEP program, e.g., as regards the conservation of beneficial organisms

Table 2. Definition of context and target parameters.

	Winter Wheat (*Triticum aestivum*)	**Table Potato (*Solanum tuberosum*)**
Context Parameters		
Region in Switzerland	Western and eastern section of the plain region	
Cultivar and use	"Top" soft wheat with low susceptibility to *Fusarium graminearum* used for bread production	"Agria" used for consumption, not for seed production
Plant density (plants/m^2)	350	5
Damage threshold for pests	Exceeded for cereal leaf beetle (*Oulema melanopus*), *i.e.*, at least 1 beetle larva per stem (corresponds to medium pest pressure)	Exceeded for Colorado potato beetle (*Leptinotarsa decemlineata*) and for potato aphids, *i.e.*, more than 40% of the leaf area is damaged in certain areas of the field (corresponds to medium pest pressure) Threshold also exceeded for aphids
Pressure by fungal diseases and weeds	Medium, threshold exceeded	Medium, threshold exceeded
Distance to water (m)	6	
Drift reduction effect due to drift reducing nozzle (%)	40	
Soil management	Plough	
Fertilizer: N, P_2O_5, K_2O, Mg (kg/ha)	140, 60, 80, 15	150, 85, 300, 25
Producer price (CHF/dt)	52.00	42.70

Table 2. *Cont.*

	Winter Wheat (*Triticum aestivum*)	Table Potato (*Solanum tuberosum*)
Target Parameters		
Yield potential, in case of no yield losses due to pest and disease damage (dt/ha) (average, multi-annual expectation)	80.0	450.0
Crop protection efficacy, expressed in percentage of yield potential (%) (average, multi-annual)	95	85
Resistance management	Low risk of leaf beetle (*Oulema melanopus*) resistance development to the applied insecticides. Resistance monitoring necessary for Colorado potato beetle (*Leptinotarsa decemlineata*).	
Side effects on bee and bumblebee	Must be avoided as far as possible	

dt = 100 kg.

2.3.1. Damage Threshold

The Swiss PEP defines the damage threshold for the cereal leaf beetle (*Oulema melanopus*) in winter wheat as one larva per stem. Since the efficacy of insecticides may vary according to pest pressure level, the following pest pressure levels are defined: medium pressure: 1–5 larva per plant; high pressure: 5–10 larva per plant; very high pressure: >10 larva per plant [21].

2.3.2. Yield Potential

The expert group thus defined 80 dt/ha as the potential yield for winter wheat, which is the theoretical yield if no pest or disease damage should occur. The experts defined 95% efficacy of pesticides as a target that would result in a yield of 76 dt/ha. This is in line with statistical data [22] on winter wheat yields in Switzerland: from 2012 to 2014 at 15% water content the average yield was 73.4 dt/ha (mean) with a 6.3 dt/ha standard deviation, ranging from 85.7 dt/ha (maximum) to 63.6 dt/ha (minimum).

2.3.3. Resistance Management

Regarding the predominant use of a single insecticide such as *Audienz,* in one of the assessed strategies, the risk of insecticide resistance development requires some consideration. In the case of the cereal leaf beetle, the expert group concluded that this risk would be very low, given that approximately 50% of the winter wheat production area in Switzerland is managed according to the principles of the "extenso program", according to which farmers apply no insecticides or fungicides, receiving additional subsidies to compensate for the expected higher yield losses. Infestations, albeit at a low level, are abundant in extenso plots, leading to a genetic pool not under selection pressure for insecticide resistance. In addition, it should not be forgotten that where pressure from the cereal leaf beetle is low, one treatment with *Nomolt* provides acceptable protection. By contrast, in potato crops, where tolerance for Colorado potato beetle damage is very low, farmers would in practice rarely rely on *Nomolt* or *Novodor* alone, and would primarily use *Audienz*. Although the IRAC (Insecticide Resistance Action Committee, http://www.irac-online.org/) has not yet reported on Colorado potato beetle resistance against spinosad, the active ingredient of *Audienz*, the risk of resistance must be considered to be increased, and evidence of resistance should be monitored.

2.3.4. Side-Effects on Bees and Bumblebees

Bee and bumblebee toxicity was meant as an important sustainability attribute. Therefore bees were included as indicator organisms in the SYNOPS ecotoxicity risk assessment. The exposure of bees to pesticides in winter wheat or potato fields can be rated as very low, however, since bees do not occur in substantial numbers in winter wheat [23], and potato crops are not a preferred host for bees, although EFSA guidance documents do not rule out a potential risk for bees and bumblebees foraging for pollen in potatoes [24]. A residual risk remains when the flower supply in the region is generally low and when bees are attracted by the honeydew from an aphid infestation in winter wheat or potato crops. The same holds true for bumblebees. Nevertheless, non-lethal side-effects on bees, bumblebees, or antagonistic arthropods might occur in very rare cases [25].

2.4. Definition of Plant Protection Strategies

The expert group defined practical plant protection schedules, bearing in mind the established contextual and target parameters. For the choice of insecticides, three basic strategies for preserving of beneficial arthropods were defined:

- **A-strategies**: Without restrictions, *i.e.*, all insecticides approved in 2012 may be used under PEP production without a special permit.
- **B-strategies**: Restrictive. Only those approved insecticides not requiring a special permit for PEP in 2012 may be used. No permits granted for exceptions.
- **C-strategies**: Special-permit practice as typical for 2012: permits are granted for treatments with insecticides with restricted use under PEP when the damage threshold has been exceeded and farmers or advisors provide evidence that the use of non-restricted insecticides would no longer have sufficient efficacy against the larvae of the cereal leaf beetle and Colorado potato beetle.

Plant protection strategies defined by the expert group concern the dose of the applied active ingredient, its cost, the associated yield risk, and the number of applications (Table 3). Only the insecticides were varied: for fungicides, herbicides, and growth regulators, the same assumptions were applied for all strategies within a crop. Since in practice the insecticides can often be applied in a tank mixture with a fungicide, the number of treatment journeys is often smaller than the number of plant protection products applied. In each case, the combination that the expert group deemed to be most frequently used in practice was chosen as the reference.

The expert group estimated the efficacy of the winter wheat reference B1 strategy (*Nomolt* and *Biscaya*) and the A1strategy (*Biscaya*) at 95%, meaning that the expected yield is 5% lower than the potential yield. This estimate is based on several years of farmers' experience with these insecticides [21]. For the strategy based on *Audienz* (B2 strategy), to date there have only been limited and very rare experiences at the farm level of a lower efficacy for *Audienz* than for *Biscaya*. The expert group estimated a 93% efficacy for *Audienz*, knowing that this estimate is uncertain. We therefore tested the robustness of the *Audienz* strategy (B2) with a sensitivity analysis.

For potatoes, since *Audienz* and *Biscaya* have been used in practice for years, the yield assumptions and rating of the efficacy of insecticides were based on field experience.

2.5. Quantitative Analysis Methods

Quantitative assessment methods were chosen according to the aim of the study to assess the effect of plant protection strategies on (i) beneficial arthropods; (ii) terrestrial and aquatic risk; and (iii) economic performance.

Table 3. Definition of plant protection strategies, based on the assumption that the tolerance thresholds are exceeded for the cereal leaf beetle (*Oulema melanopus*), Colorado potato beetle (*Leptinotarsa decemlineata*), and potato aphids.

Crop Protection Strategy	Insecticide (Trade Name)	Active Ingredient (g/ha)	Cost of Insecticide (CHF/ha)	Crop Protection Efficacy (*i.e.*, expected Yield in Percentage of Yield Potential)	Fungicide/Herbicide/ Molting Inhibitor (Number of Applications)	Spray Tank Mix (Number)	Drive through (Number)
				Winter Wheat			
A1	Biscaya *	58	33	95%	2/1/1	1	4
B1	Nomolt and Audienz *	60 and 48	78 and 62	93%	2/1/1	1	5
B2	Audienz *	48	62	93%	2/1/1	1	4
C1 Reference	Nomolt and Biscaya *	60 and 58	78 and 33	95%	2/1/1	1	4
				Potato			
A1	Karate * and Biscaya *	8 and 48	18 and 33	85%	13/2/0	3	14
A2	Biscaya * (2×)	48 (2×)	33 (2×)	85%	13/2/0	3	14
B1	Nomolt, Audienz and Plenum *	38, 24 and 150	49, 31 and 84	85%	13/2/0	4	14
B2	Novodor, Audienz and Plenum *	120, 24 and 150	192, 31 and 84	85%	13/2/0	4	14
B3	Novodor (2×) and Plenum *	120 (2×) and 150	192 (2×) and 84	80%	13/2/0	4	14
C1 Reference (CPB ≠ PA)	Audienz and Plenum *	24 and 150	31 and 84	85%	13/2/0	3	14
C2 (CPB + PA)	Audienz and Biscaya *	24 and 48	31 and 33	85%	13/2/0	3	14

* Insecticides requiring a special permit under the Proof of Ecological Performance (PEP) rule in 2012. (CPB ≠ PA): Colorado potato beetles (CPB) are not present concurrently with potato aphids (PA). (CPB + PA): Colorado potato beetles are present at the same time as potato aphids. Insecticides in winter wheat: applied to control cereal leaf beetle; insecticides in potatoes: applied to control Colorado beetle and aphids. Trade name (active ingredient/category) for insecticides: ***Audienz*** (spinosad/spinosyn); ***Biscaya*** (thiacloprid/neonicotinoids); ***Karate*** (lambda-cyhalothrin/pyrethroids); ***Nomolt*** (teflubenzuron/molting inhibitors); ***Novodor*** (*Bacillus thuringiensis*/biopesticides); ***Plenum*** (pymetrozine/pyridine-azomethrines). For fungal diseases and weeds, medium pressure was assumed. Number of treatments with fungicides/herbicides/growth regulators in winter wheat (identical treatment schedule for all variants): 2/1/1, with the following fungicides: Amistar Xtra (azoxystrobin, cyproconazole); Input (spiroxamin, prothioconazole). Number of treatments with fungicides/herbicides in potatoes with identical treatment schedule for all strategies: 13/2, with the following fungicide: 7 × Mancozeb (= 4.5 × full dose). Prices refer to the years 2009–2011 in Switzerland and are average prices without discount. x is used as multiplication sign, e.g., 48 (2×) = 96 g/ha were applied, two applications with 48 g/ha each.

The method for assessing the influence of insecticides on beneficial arthropods in winter wheat and potatoes is described in detail in [12]. Among the taxa of insects known as antagonists of the pest insects (*i.e.*, beneficial insects), *Coccinellidae*, *Chrysopidae*, *Syrphidae and Hymenoptera-parasitoids* were included in the assessment, since these taxa are of potential relevance in the regulation of pest populations in either winter wheat or potatoes, as well as being potentially abundant in these crops at the time when chemical treatments to control these pests take place [12,14]. The mortality impact of the applied insecticides on these taxa was rated on the basis of data available from different sources, such as, for example, [26] or [11]. The expected effects of repeat treatments or combinations of insecticides were also taken into account according to a rating scheme described in [12].

The "SYNOPS model," developed at the Julius Kühn Institute in Germany [27], was used to analyze the ecological risk for soil and water organisms. SYNOPS assesses the risk for organisms living in terrestrial habitats (*i.e.*, soil and field margins) and aquatic habitats (*i.e.*, surface water). It combines pesticide-use data, including degrees of drift-reduction measures, with environmental conditions (e.g., distance from field to surface water). The chemical, physical, and eco-toxicological properties of applied active ingredients are taken into account [28,29]. In general, the acute and chronic risk potentials are calculated for reference organisms such as earthworms for soil and Daphnia, algae, and fish for surface water. Time-dependent pesticide concentration curves are used to determine the acute and chronic risk potentials by relating pesticide concentration in the environment to the lethal concentration (LC_{50}) and the no-effect concentration (NOEC). For the risk assessment, the ratio is used between the toxicity of active agents for these groups of organisms and the concentration of the active agent (exposure). This yields the exposure-toxicity ratio (ETR), expressed as a measure of the risk, with ETR = exposure/toxicity. The following sustainability attributes were derived from the SYNOPS assessment in this study: acute terrestrial risk; chronic terrestrial risk; acute aquatic risk; and chronic aquatic risk.

For the economic analysis, a full-cost calculation was carried out for each plant protection strategy. The full-cost calculation compares the revenue, consisting of receipts and direct payments, with the total production costs, consisting of direct and structural costs, in order to determine profits or losses. If, for example, the profit threshold is reached precisely, this means that the total production costs are covered, including the assumed wage entitlement of CHF 28/h [30]. Similarly, a calculated working income of over CHF 28/h means that a profit has been generated. In addition to the cost of materials, the total plant protection costs also include labor, machinery, and infrastructure costs [30], which is why the number of journeys significantly influences costs.

2.6. Sustainability Assessment

Figure 1c,d shows the assessment tree used in this study. Attributes are hierarchically arranged according to the SustainOS approach [18]. The basic attributes (grey) refer to the results of the quantitative analyses. Only the basic attribute "yield risk" was estimated by the expert group. No LCA was carried out in this study, since the strategies hardly differed with respect to energy and resource consumption. The ecological and economic attributes are on the left and right sides of the assessment tree, respectively. All attributes of the assessment tree were weighted evenly, with the exception of the chronic and acute risk, weighted at 67% and 33%, respectively. The chronic risk was weighted higher because in winter wheat and potato-growing practice, the higher concentrations necessary for acute effects occur less frequently than the on-the-whole lower concentrations associated with the potential chronic risks.

In order to convert the quantitative results of the analyses into basic attributes to be assessed, five assessment categories were used relative to the reference strategy (RS): 1 = Much worse than RS; 2 = Worse than RS; 3 = Similar to RS; 4 = Better than RS; 5 = Much better than RS.

The basic attributes of economic sustainability (production costs per ha, income per ha, and yield risk) were assigned to sustainability categories 1 to 5 based on their effect on the income, expressed as an hourly wage. Yield risk was related directly to the estimated efficacy of crop protection strategies (Table 2). The expert group defined ±5% compared to the RS for assessment categories 2 and 4 and ±20% compared to the RS for assessment categories 1 and 5 as the limits for a significant difference in this income parameter. Where the hourly wage differed less than ±5% from the reference, it was assigned to assessment category 3 (similar to the RS). Since the imputed hourly wage of the reference strategy was CHF 25 for winter wheat and CHF 39 for potatoes, the following scales for delimiting the sustainability assessment were yielded per crop:

- Winter wheat: Limits for categories 4 and 5 (better and much better than RS, respectively), where costs are CHF 66 and CHF 266/ha lower than RS, respectively; limits for categories 2 and 1 (worse and much worse than RS, respectively), where costs are CHF 67 and CHF 266/ha higher than RS, respectively. Total RS production costs: CHF 5596/ha.
- Potatoes: Limits for categories 4 and 5, where costs are CHF 163 and CHF 968/ha lower than RS, respectively; limits for categories 2 and 1, where costs are CHF 240 and CHF 1024/ha higher than RS. Total RS production costs: CHF 17,483/ha.

2.7. Sensitivity Analysis Method

The efficacy of insecticides directly affects yield, which, together with crop price, is the most sensitive economic variable, much more sensitive than costs for pest control [31,32]. For winter wheat, however, the efficacy of *Audienz* is uncertain. A sensitivity analysis was therefore conducted to test the robustness of the economic sustainability rating results if the efficacy of *Audienz* were lower than estimated by the expert group. Consequently, we calculated the efficacy for which the hourly income changes from similar to reference to worse (minus 5% of hourly income) and much worse (minus 20% of hourly income). For these calculations, we used the full-cost calculation scheme described above. We also derived the respective yield and production costs as well as the associated rating results for economic sustainability from these calculations.

3**. Results**

3.1. Results for Winter Wheat

3.1.1. Sustainability Assessment Results

According to the experts' experience, the situation under the 2012 PEP requirements is well illustrated by the reference strategy (C1), in which first the molting inhibitor *Nomolt* and then (for infestations higher than the tolerance threshold and after obtaining the special permit) the neonicotinoid *Biscaya* is used against the cereal leaf beetle. The analysis of the reference shows that *Nomolt* is sometimes not reliably effective against cereal leaf beetle larvae since adequate efficacy is limited to young larvae only, and that although *Biscaya* achieves very good efficacy, it also causes significant harm to beneficial species. The overall ecological/economic sustainability of this reference is surpassed by two of the three alternative strategies—strategies B2 (*Audienz*) and A1 (*Biscaya*)—which Figure 2a shows as achieving ratings clearly above 3.0 for overall sustainability. The overall sustainability of strategy B1 (*Nomolt* and *Audienz*) is slightly worse than that of the reference. Figure 2b–d enable us to follow the results for overall sustainability in terms of the lower attribute levels. It is interesting to note that, for very different reasons, the two best strategies are rated as better than the reference in terms of overall sustainability. Strategy B2 (*Audienz*) has a strong advantage over the reference in terms of ecological sustainability, for which it has a rating of 4.33 (Figure 2b). This is due to a much better preservation of beneficial species (5.0) and a better ecological risk rating (3.67) (Figure 2c). In terms of economic attributes, however, B2 (*Audienz*) has both advantages and disadvantages with respect to the reference. Whereas the yield risk is higher, and the anticipated yield is therefore smaller (Figure 2d), production costs are also lower, since one pass (CHF 77/ha for machinery and labor) and the costs for *Nomolt* (CHF 78/ha) are absent. Given that this cost advantage is just canceled out by the lower revenues (lower yields), the result is an income that does not differ significantly from the reference.

With strategy A1, where, in contrast to the reference, *Nomolt* is not applied, the good efficacy of *Biscaya* results in a yield risk identical to that of the reference. Consequently, the cost advantage (no *Nomolt* and one fewer journey) achieves a correspondingly better income (Figure 2d).

3.1.2. Sensitivity Analysis Results for Efficacy of Insecticides Affecting Income

The results of the sensitivity analysis are presented in Table 4. Our sensitivity analysis showed that when the efficacy of the strategy based on *Audienz* (strategy B2) decreased slightly, *i.e.*, from 93.0% to 90.0% or 85.5%, the rating changed from "similar to reference" to "worse than reference" or "much worse than reference," respectively. This means that insecticide efficacy is a highly sensitive parameter for economic sustainability, because it significantly influences economic attributes by affecting changes in yield.

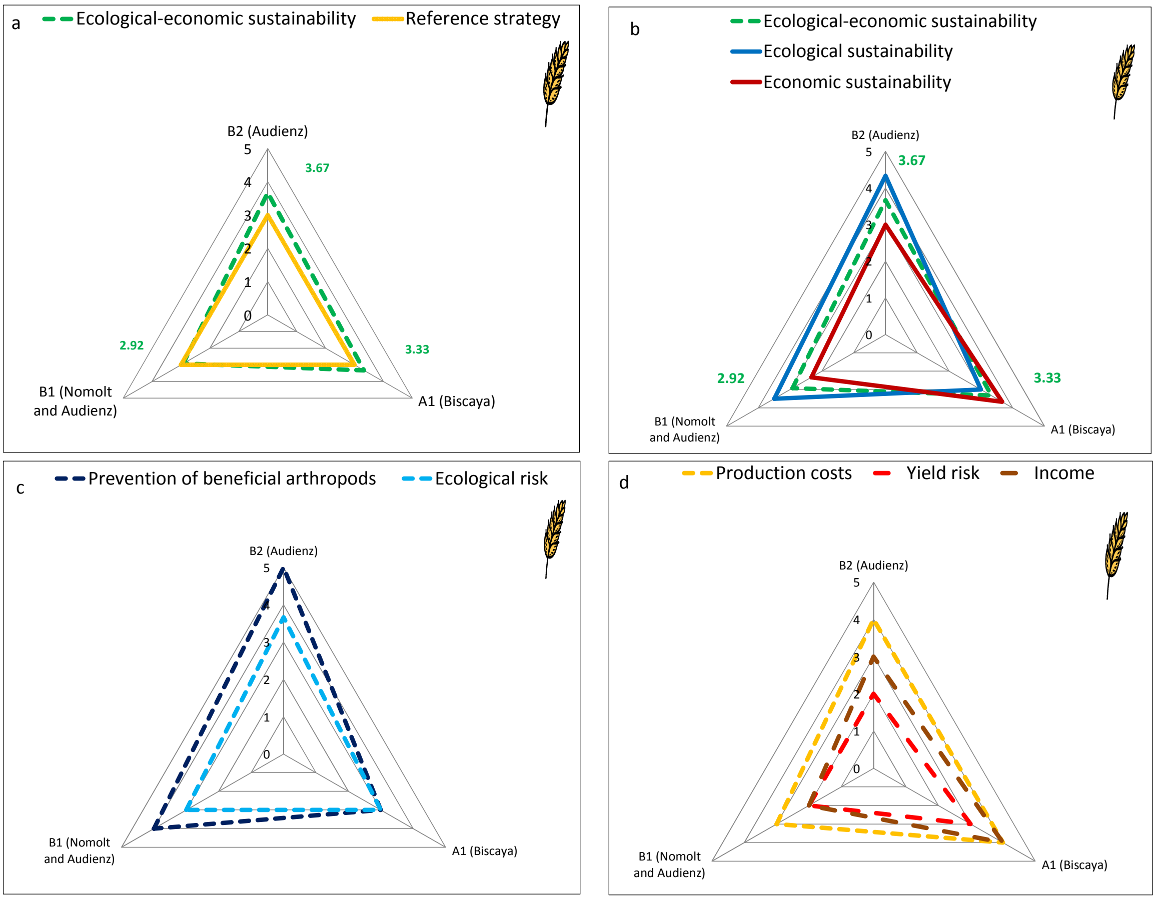

Figure 2. Results of the sustainability assessment of different plant protection strategies for the control of the cereal leaf beetle compared to the reference strategy using *Nomolt* (teflubenzuron) and *Biscaya* (thiacloprid). 1 = Much worse than RS; 2 = Worse than RS; 3 = Similar to RS; 4 = Better than RS; 5 = Much better than RS; RS = Reference strategy.

Table 4. Sensitivity analysis of *Audienz's* efficacy for the control of the cereal leaf beetle (*Oulema melanopus*) in winter wheat.

	Income			Yield		Yield risk		Sustainability ratings		
Plant protection strategy	CHF/h		Rating	dt/ha		Efficacy (expected yield in percentage of potential yield, *i.e.*, 80.0 dt/ha)	Rating	Economic	Ecological	Overall sustainability
Reference (Nomolt and Biscaya) According to expert group	36.44	100.0%	3.00	76.00	100.0%	95.0%	3.00	3.00	3.00	3.00
A1 (Biscaya) According to expert group	41.48	113.8%	4.00	76.00	100.0%	95.0%	3.00	3.67	3.00	3.33
B2 (Audienz) According to expert group	38.18	104.8%	3.00	74.40	97.9%	93.0%	2.00	3.00	4.33	3.67
B2 (Audienz) **Sensitivity secenario:** Income per hour 5% lower than reference	34.62	95.0%	2.00	72.03	94.8%	90.04%	2.00	2.67	4.33	3.50
B2 (Audienz) **Sensitivity secenario**: Income 20% lower than reference	29.15	80.0%	1.00	68.40	90.0%	85.49%	1.00	2.00	4.33	3.17

Rating categories: 1 = Much worse than RS; 2 = Worse than RS; 3 = Similar to RS; 4 = Better than RS; 5 = Much better than RS; RS = Reference strategy. Rating results of the sensitivity analysis that are lower than the ratings based on 93% efficacy assumed by the expert group are highlighted in yellow.

3.2. Results for Potatoes

The reference strategy (C1), which illustrates current practice as part of the 2012 PEP conditions, involves one treatment with *Audienz* for the Colorado potato beetle (no special permit necessary) and one treatment with *Plenum* for aphids (special permit required), assuming that the damage threshold has been exceeded for both pests. None of the six alternative strategies tested surpasses the overall ecological-economic sustainability of the reference strategy. Among the alternative strategies, strategy B2—in which, unlike in the reference, the bioinsecticide *Novodor* (*Bacillus thuringiensis*) is also used before the application of *Audienz*—achieves the best overall sustainability rating of 3.0, which is as good as the reference (Figure 3a). Figure 3b,c show that strategy B2 does not differ significantly from the reference in terms of all sub-attributes either, since these all have ratings of 3.0. In terms of the production costs this may come as something of a surprise, since B2 also involves a treatment with *Novodor* that is absent from the reference. In fact, while all strategies have a total of 14 journeys due to frequent fungicide applications, the Novodor product costs amount to an additional CHF 192/ha, which, however, corresponds to a loss of less than 5% in income. There are no additional costs for machinery and labor, since 14 journeys per hectare and year were defined for both reference and all alternative strategies, and additional insecticides can in practice be applied as a tank mixture together with fungicides.

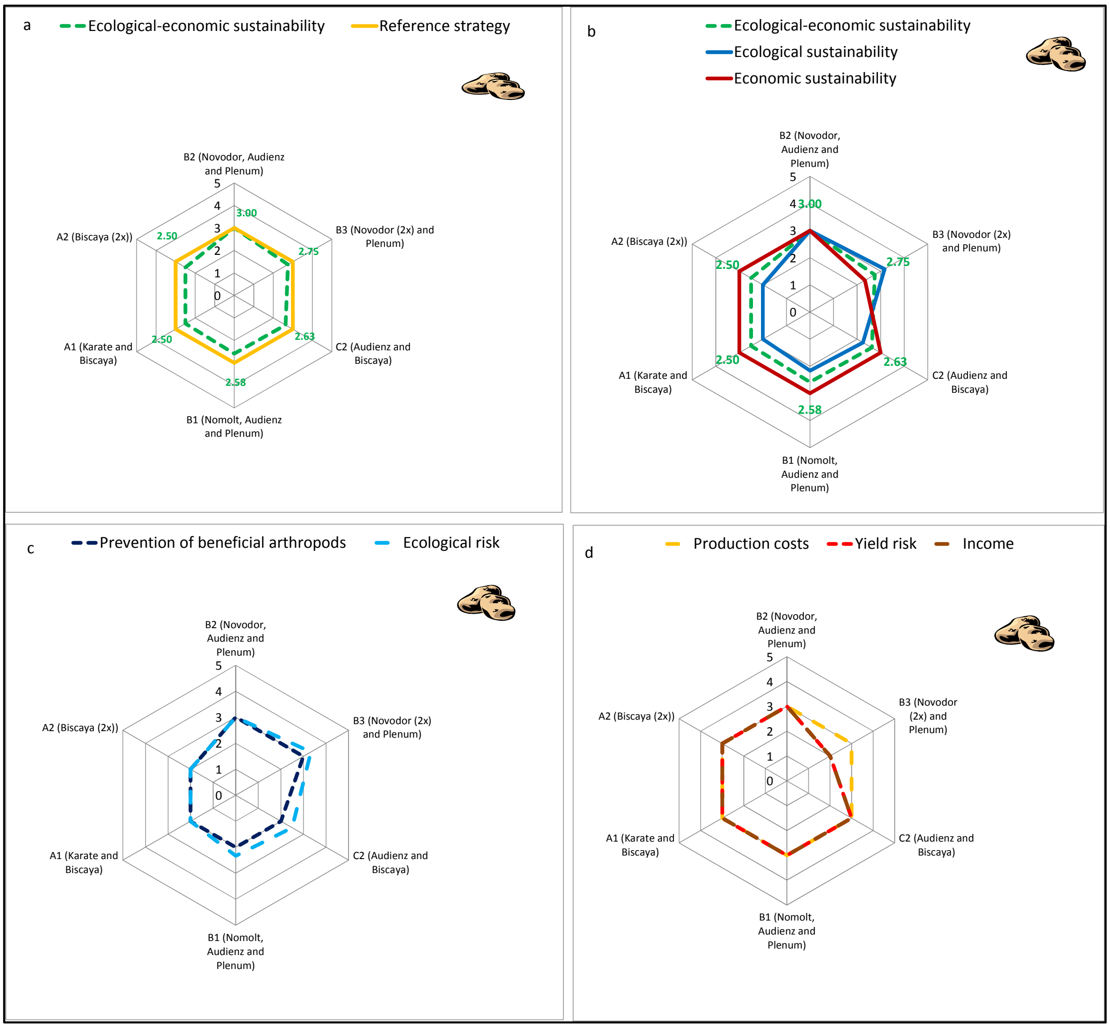

Figure 3. Results of the sustainability assessment of different plant protection strategies for the control of Colorado potato beetles and potato aphids compared to the reference strategy using *Audienz* (spinosad) and *Plenum* (pymetrozine). 1 = Much worse than RS; 2 = Worse than RS; 3 = Similar to RS; 4 = Better than RS; 5 = Much better than RS; RS = Reference strategy.

Strategy B3 (*Novodor* × 2 and *Plenum*), which, unlike the reference, uses *Novodor* twice instead of *Audienz* once for the Colorado potato beetle, achieves an overall sustainability rating of 2.75 (Figure 3a), although with two applications of *Novodor* it has advantages over the reference in terms of ecological risk (3.33), and performs the same as the reference in terms of the preservation of beneficial species (Figure 3c). These ecological advantages are, however, offset by additional costs of CHF 353/ha. Since, however, there are no advantages in terms of yield risk, income is also lower than in the reference. All in all, the economic disadvantages of strategy B3 vis-a-vis the reference outweigh the ecological advantages (Figure 3b).

The remaining four alternatives (C2, B1, A1, and A2) all have the same profile. None of them differs significantly from the reference in terms of cost-effectiveness, while they all exhibit clear disadvantages in terms of ecological sustainability (Figure 3b,c).

In the strategies studied, the insecticide *Plenum* (Pymetrozine) was used against aphids in potato crops. Alternatively, *Teppeki* (Flonicamid) can be used here. Both *Plenum* and *Teppeki* can be classified as 'neutral' in terms of the side-effects on beneficial species [5].

4. Discussion

This study shows that if the respective damage threshold is exceeded, the use of *Audienz* against both the cereal leaf beetle and the Colorado potato beetle protects beneficial arthropods better than *Biscaya*, and hence *Audienz* better fulfills the aim of the Swiss PEP requirement for preservation of beneficial arthropods. Moreover, if further attributes—economic as well as environmental—are considered in addition to the preservation of beneficial arthropods, the use of *Audienz* results in a better overall sustainability than the use of *Biscaya*. Since insecticide resistance management and a low risk for bees and bumblebees were target parameters in the expert approach, these issues are also considered in the sustainability rating of these strategies.

The sensitivity analysis demonstrated that insecticide efficacy is a highly sensitive parameter for economic sustainability, because it significantly influences economic attributes by affecting changes in yield [31,33]. However, growers' experiences from the 2015 field season indicate that, in situations with high pest pressure, *i.e.*, infestations of >10 larvae per stem, application of *Audienz* alone may not provide sufficient control, which according to the sensitivity analysis would have a significant negative impact on the economic sustainability of this strategy. Should further experience and field assays corroborate these findings, close monitoring of the development of pest populations and—in cases of high pest pressure—application for a special permit to apply *Biscaya* might help farmers avoid economically important yield losses. Since these cases are expected to be fairly exceptional, they would not greatly impair performance along the ecological sustainability axis.

The SustainOS approach, which combines expert knowledge with quantitative assessment methods, turned out to be a suitable scheme given the lack of approved field data for many parameters. The goal of the study was to address a few key pests while keeping context and target parameters (e.g., pest and disease pressure, fertilizer, machinery use) constant for all crop protection strategies. The assessment was based on eight basic and five aggregated attributes. SustainOS uses a procedure to construct an attribute tree that fits specific assessment goals and data availability. In cases where few data are available, it is recommended to use a relatively simple set of indicators [33]. DEXiPM [34,35] is another approach for conducting sustainability assessments that has recently been applied in Europe. This approach includes a fixed set of 75 basic and 86 aggregated attributes and thus requires more input parameters and more data availability compared with SustainOS. Both approaches have in common the fact that missing data can be replaced by experts' estimations.

While assessing reports for this study, it became evident that ecotoxicological data from the insecticide registration dossiers are readily accessible, and that considerable information regarding the impact of insecticides on non-target and beneficial arthropods is also available (see references in Introduction). Studies comparing insecticides vis-à-vis their impact on beneficial species in cropping systems, and in particular in terms of their pest control capacity in real field situations, however, are in short supply. In many cases, the only available field studies were conducted a decade or more ago, addressing other pesticides in winter wheat than the ones that are in use today [36]. The complexity of consideration is illustrated by the case of the chemical group of spinosyns, which includes *Audienz*. A review [37] showed that for most arthropod taxa there is evidence of adverse effects of spinosyns, but results may be inconsistent, depending on a wide variety of parameters. In order to better understand the effect of programs such as PEP on functional biodiversity within arable crop fields, more studies are needed. Furthermore, it cannot be ruled out that fungicides (especially in the case of repeated applications in the same field and year, as is typical for potato cultivation) may also have negative effects on beneficial arthropods. Here, too, few field data are available on this topic. Since integrated pest management (IPM) is being introduced across the board in all EU countries from 2014 onwards, field data on the preservation of beneficial arthropods will in general be met with greater interest now, both from users and from plant protection product manufacturers.

5. Conclusions

The sustainability assessment of this study investigated various practical plant protection strategies, based on the assumption that the damage thresholds for the cereal leaf beetle in winter wheat and the Colorado potato beetle and potato aphids in table-potato crops had been exceeded, and that insecticide treatments were therefore unavoidable. Essentially, the issue comes down to a comparison of the two insecticides *Audienz* (spinosad/spinosyn) and *Biscaya* (thiacloprid/neonicotinoid). The following recommendations for the PEP requirements can be made based on this study:

- For winter wheat, among the assessed insecticides, *Audienz* (spinosad) can be approved for use within PEP against the cereal leaf beetle without a special permit. By contrast, a special permit should continue to be stipulated for *Biscaya* (thiacloprid), since the available data suggest that this insecticide has a higher overall risk of harming beneficial arthropods and a higher risk for terrestrial and aquatic organisms. The advantage of *Audienz* over *Biscaya* in terms of preservation of beneficial arthropods is offset by the slight economic drawbacks. Viewed across all of the assessed attributes, however, *Audienz* boasts the best sustainability.
- With regard to the control of the Colorado potato beetle, it was confirmed that allowing the application of *Audienz* without a special permit would be justified, and that this would result in better preservation of beneficial arthropods in the crop and a lower ecological risk for terrestrial and aquatic organisms than if *Biscaya* were used. The two insecticides *Plenum* and *Teppeki* were recently approved for controlling aphids in potatoes within PEP requirements, since their use in the overall system neither additionally harms beneficial arthropods nor increases ecological risks.

Our experience shows that the SustainOS approach, originally developed for comparing the sustainability of crop protection strategies in orchard systems, offers a practicable scheme that can also be applied to arable crops.

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