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Indicator-based agri-environmental direct payments: Assessment of three systems of different complexity levels

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ABSTRACT

This paper presents a scientifically sound set of environmental indicators for comprehensive description of farm environmental impact within a policy-driven framework that aims at achieving Swiss agri-environmental policy goals. The indicator system covers the following key environmental areas: greenhouse gas (GHG) and ammonia emissions, nitrate and phosphorus leaching, biodiversity, plant protection products, soil erosion, and humus accumulation. Novel indicators were developed through reviewing existing indicators and intensive consultation with experts. To provide a flexible and suitable indicator-based system, three systems of varying complexity (simple, medium, detailed) were developed.

In-depth evaluation revealed specific advantages and disadvantages of the three novel indicator systems at different complexity levels. The simple system benefited from a low administrative burden, but may suffer from limited acceptance owing to its low flexibility regarding farmers' scope for action. The detailed system may be very demanding to implement in terms of data acquisition, but benefited from more accurate representation of the key driving processes. Successful implementation of the system will require broad acceptance promoted through sufficient support and advice, good communication between participating stakeholders, a secure and simple data acquisition process, and a high degree of transparency.

1. Introduction

Expansion of food production to meet rising global demand is associated with substantial negative environmental impacts and increasing use of resources such as land, fresh water, nutrients, and energy (Struik and Kuyper 2017). Food production is a major driver of global environmental degradation and has contributed to humanity already exceeding some major environmental planetary boundaries (Rockström et al. 2009): The boundaries for biodiversity loss, climate change, and phosphorus and nitrogen cycling have already been significantly exceeded. For example, the current phosphorus application rate to cropland is 14.2 Tg P/year, which is 268 % higher than the planetary boundary (5.3 Tg P/year) (Steffen et al. 2015). To keep human activities within planetary boundaries, a strong shift is required towards more efficient agricultural production with optimized use of land, water, nutrients, and energy. In the past, agricultural subsidies were paid to help farmers make a reasonable living, to enhance agricultural productivity, and to support the rural economy (Dethier and Effenberger 2012). However, because agricultural production contributes significantly to the global environmental burden imposed by humans, many developed countries have moved away from paying incentives for production of commodities towards fiscal subsidies that ensure environmental sustainability without reducing production (Mamun et al. 2021). Many countries are re-designing their agricultural support schemes in

Abbreviations: AEO, Agri-Environmental Objectives; CH_4, Methane; CO_2, Carbon Dioxide; CO_2-eq, Carbon Dioxide Equivalent; EF, Emission Factor; GHG, Greenhouse Gas; GWP, Global Warming Potential; IBDP, Indicator-Based Direct Payments; KSNL, Kriteriensystem nachhaltige Landwirtschaft (criteria system for sustainable agriculture); LCI, Life Cycle Inventory; LCIA, Life Cycle Impact Assessment; LU, Livestock Unit; N, Nitrogen; N_2O, Nitrous Oxide; PPP, Plant Protection Product(s); RISE, Response-Inducing Sustainability Evaluation; RS, Risk Score; RUSLE, Revised Universal Soil Loss Equation; SALCA, Swiss Agricultural Life Cycle Assessment; SMART, Sustainability Monitoring and Assessment Routine; SOC, Soil Organic Carbon; UAA, Utilized Agricultural Area.

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order to promote more environmentally friendly agricultural practices, thereby transforming the agriculture sector (Piñeiro et al. 2020). For example, reduced environmental impacts through subsidization of climate-smart production approaches (Engel and Muller 2016), such as agroforestry, application of biochar, and compost-induced carbon sequestration, can be expected.

Switzerland must contribute its share to the ambitious international goals aimed at reducing negative human impacts on the environment. Based on current domestic targets as formulated in the Sustainable Development Strategy 2030, the total environmental impact of human activities in Switzerland (only greenhouse gases (GHG), eutrophication, and biodiversity are considered here) must be reduced by approximately 67 % in order to avoid exceeding the planet's carrying capacity (EBP 2022). Reductions in nitrogen surpluses are crucial to reduce eutrophication of terrestrial and aquatic ecosystems and nitrate in groundwater. Using spatially explicit models, Schulte-Uebbing et al. (2022) showed that planetary nitrogen boundaries should be complemented by regional planetary boundaries, to account for spatial variability in ecosystem sensitivity to nitrogen pollution and in agricultural nitrogen losses.

In 2019, the Swiss Federal Council decided that Switzerland should halve its GHG emissions by 2030, and achieve net-zero GHG emissions by 2050. The agriculture sector must contribute to this goal through reducing its GHG emissions by 22 % by 2030 compared with 1990 (Bretscher et al. 2018). To ensure clean drinking water, the risks associated with use of plant protection products (PPP) must be halved by 2027 and nitrogen and phosphorus surpluses must be reduced by at least 20 % by 2030. A first package of regulations to achieve these goals was adopted by the Federal Council in 2022.

Switzerland has a multifunctional subsidy scheme (Hediger 2006) that aims to promote secure provision of food, conservation of natural resources, and maintenance of the rural landscape. The Swiss government has established agri-environmental objectives (AEOs) for the farming sector as part of its constitutional mandate to promote sustainable and resource-efficient agricultural production (FOEN and FOAG, 2008). Although payment of government subsidies (direct payments) is already tied to cross-compliance standards, the AEOs have largely not been met (FOEN and FOAG, 2016).

Against this background, a project was established to develop an indicator-based direct payments (IBDP) system, as one option for reducing the negative environmental impacts of the Swiss agriculture sector. The IBDP system is novel and, with a few exceptions such as biodiversity (see Gilgen et al. 2022b), it is not based on the current direct payment system. Indicators are used to simplify, quantify, analyze, and communicate otherwise complex and complicated information, and to summarize various aspects of complex issues into a simple score. Use of indicators is thus a powerful tool for condensing information to support decision-making and policy-relevant applications (Singh et al. 2009). It also permits horizontal comparisons of an issue between different farms (e.g., comparing eutrophication for a number of selected pilot farms), and vertical comparisons for verification of temporal changes in a particular system (e.g., in nitrogen leaching over time). To increase the flexibility of the system, three systems of different complexity levels (simple, medium, detailed) were developed.

A comprehensive assessment was then performed on the potential of environmental indicators for agri-environmental policy. This assessment included (i) determining why existing indicator systems are not suitable for use within the given policy context, (ii) detailed description of the new IBDP indicators, (iii) thorough assessment of advantages and disadvantages of the IBDP system, (iv) evaluation of expected challenges and recommended solutions, and (v) evaluation of the completeness, reproducibility, and applicability (communicability and practicability) of three systems at different complexity levels (simple, medium, detailed).

The remainder of this paper is structured as follows: Section 2 presents the methodology and Section 3 provides a detailed description of the three IBDP systems of different complexity. In Section 4, advantages and disadvantages of the IBDP systems are discussed in detail. Finally, some conclusions are presented in Section 5.

2. Methodology

2.1. Development of indicators for the new IBDP system

Development of new indicators is a challenging task because it requires a clear concept and understanding of the processes involved (Radermacher 2021). When designing an indicator, its purpose first needs to be clearly defined, which requires e.g., explicit formulation of the IBDP target group. This group may include the entire agriculture sector, and policymakers and consumers interested in minimizing the fiscal burden and environmental impact of the food sector. The IBDP framework was designed to link the environmental impacts of farms directly to the amount of subsidies paid to the farmer.

2.2. Suitability of existing indicators for the new IBDP system

Before developing the IBDP system with its three different levels of complexity, we performed an analysis of existing indicator-based sustainability systems. The results revealed that existing approaches were unlikely to be suitable for our purposes. Life cycle impact assessment (LCIA) indicators at the midpoint or endpoint level were rejected for use in the IBDP system for various reasons. For example, Swiss Agricultural Life Cycle Assessment (SALCA) requires a large amount of input data to build comprehensive life cycle inventories (LCI), covering all relevant environmental categories (Gaillard and Nemecek 2009). In addition, in order to run the SALCA model, detailed agricultural management data on e.g. machinery use, feeding, fertilizer and PPP applications, timing of interventions, and water use are required, partly at the plot level (Gaillard and Nemecek 2009). Acquisition of such data is far too time-consuming within the context of a policy-driven framework. Moreover, in order to meet the necessary quality standards, the time-consuming data collection step must be followed by a comprehensive plausibility check, to avoid unintentional and deliberate misreporting, but plausibility checks are extremely time-consuming and unable to capture all incorrect entries (Gilgen et al. 2023). In order to avoid reporting of incorrect agricultural activity data, strict and frequent *in situ* controls would be necessary, which is unrealistic within the framework of a direct payments system. Necessary adaptions of IT infrastructure and harmonization of relevant databases would also be very costly. Thus the SALCA method is not appropriate for use in an IBDP system.

Many previous studies are based on attributional LCA (aLCA), but use of consequential LCA (cLCA) has been increasing over the past few years. Finnveden et al. (2009) defined cLCA as an LCA approach aiming to describe how environmentally relevant flows change in response to possible decisions. However, cLCA increases the number of causal relationships studied, and therefore the complexity and uncertainty of the models, and has higher demands for input data. It is also more difficult for stakeholders to understand. For these reasons, cLCA is not appropriate for an IBDP system.

Very complex models that parameterize the underlying processes based on comprehensive and complex physical models are also not appropriate for use. These include the REPRO (REPROduction of soil fertility) model (Küstermann et al. 2008) developed in Germany; the Swiss Agri-Environmental Data Network, which has the main goal of agri-environmental monitoring of Swiss agriculture and which is not compatible with the IBDP system due to the overly extensive input data set required; and the MOTIFS monitoring method (Meul et al. 2008), which focuses on three areas (use of inputs, quality of natural resources, biodiversity) and lacks full coverage of all relevant environmental aspects.

Indicator systems primarily designed for consultancy purposes, such as response-inducing sustainability evaluation (RISE) (Grenz et al. 2009), sustainability monitoring and assessment routine (SMART)

(Schader et al. 2016), and the “indicateurs de durabilité des exploitations agricoles” method (Zahm et al. 2008), do not meet the policy-imposed conditions in IBDP such as sufficient scientific basis, complete coverage of environmental issues, and a manageable amount of required input data. Furthermore, indicator systems such as RISE and SMART that include qualitative subjective ratings by consultants are unsuitable for IBDP, because subjectivity is prone to unequal treatment of different farms and largely prevents third party verifiability. For example, SMART allows visual inspection by experts when estimating crop growth or the degree of soil structure deterioration (Schader et al. 2016).

Some existing indicator systems require country-specific input data, which hampers transfer to Swiss conditions. For example, the criteria system for sustainable agriculture (KSNL) system (Breitschuh et al. 2008) uses the so-called “Ackerzahl” (arable number) for classifying the quality of soils on German farms, but this does not exist in Switzerland. Parameterizations that depend on country-specific statistical data (such as median field size) or threshold and guideline values also hamper transfer from foreign frameworks to Swiss conditions. In addition, country-specific regulations (e.g., fertilizer regulations) and laws may critically reduce the transferability of indicator systems developed for countries to Swiss conditions. Moreover, data accessibility (and definition of the variables) often differs widely between countries.

In summary, our evaluation revealed that existing methods are unsuitable for agricultural policy indicators in IBDP owing to their complexity, different purposes (i.e., research, monitoring), and non-verifiability of required input data, among other factors. Furthermore, indicators primarily based on expert judgment or qualitative data, or both, should not be used in the context of agricultural policy, because it is critically important to use verifiable input data. Finally, it is important that the indicator system is structured in such a way that farmers can easily understand the changes they must make (lowering the farm’s environmental impact) to increase their direct payments. For these reasons, when developing an indicator system our focus was on simple comprehensibility and good communicability, through using a well-defined, limited set of required input data.

2.3. Development of novel indicators

We developed three indicator systems with different levels of complexity (simple, medium, detailed) in order to provide sufficient flexibility when dealing with environmental decision making and achieving environmental policy goals. Note, however, that even the detailed system was far below the level of complexity of LCIA indicators and other sophisticated complex physical models. The challenge was to find a good compromise between a flexible and feasible system. In a flexible system, the farmer can optimize several measures to achieve target reduction potential for a specific environmental impact. This system requires inclusion of a maximum of mitigation options. In contrast, a feasible system allows efficient and cheap implementation, with a reduced set of easily available and verifiable input data, and with indicators that are easily communicable to farmers, advisors, and other interested stakeholders. When selecting thematic aspects and corresponding appropriate parameterizations, we primarily considered processes (i) relevant for thematic completeness and (ii) parameterizable using a limited set of quantitative input variables that can be recorded at sufficient accuracy and verified for plausibility and falsification in a short time.

2.4. Identification of key driving processes and factors

Construction of the three indicator systems required thorough analysis of key driving processes and factors, requiring expert knowledge. Furthermore, good availability of verifiable and accurate input data that could be collected without huge time efforts had to be ensured at all three levels of complexity. Strong emphasis was placed on providing indicators that can be communicated easily to relevant stakeholders (farmers, national and cantonal agricultural agencies, agricultural extension services), while not ignoring the policy context.

In the simple system, environmental impacts are assessed in a very generic manner, even allowing the use of one single indicator to describe several environmental impacts that are driven by similar physical processes. For example, GHG emissions, ammonia emissions, and nutrient leaching are merged into one single indicator, called “climate and nutrients”. A very limited set of input parameters is sufficient as input for this simplistic approach, which minimizes the administrational effort for data acquisition and the time needed for checking data accuracy.

The detailed system aims to take the major driving factors into account, while still avoiding an overly high level of complexity. The indicators have to be sufficiently flexible to account for some specific measures taken by the farmer, i.e., they have to be sensitive enough for accurate estimation of how fully environmental policy targets will be achieved when farmers adopt a specific set of measures. The detailed system provides separate indicators for the following eight environmental areas: (i) GHG emissions, (ii) ammonia emissions, (iii) nitrate leaching, (iv) phosphorus leaching, (v) biodiversity, (vi) PPP, (vii) soil erosion, and (viii) humus accumulation.

The medium system lies between the simple and detailed system in terms of complexity, so it is more accurate, but also requires more input data, than the simple system and considers fewer processes, but greatly simplifies and speeds up data acquisition, compared with the detailed system.

Various emissions and environmental impacts show great spatial variation (Patouillard et al. 2018). For example, site-dependent factors such as topography and soil characteristics determine the amount of eroded soil particles, while nitrate leaching is influenced by soil type and water saturation. Therefore, some of the IBDP indicators consider site-specific parameters. However, we limited site-dependent input parameters (such as region, slope, soil characteristics) to the minimum, always keeping in mind that the system will be used for political purposes.

3. Results

This section is dedicated to one of the major outcomes of the project, namely the design of IBDP systems for all three complexity levels (simple, medium, detailed). We provide a detailed description for four typical examples of the novel indicators, covering: (i) GHG emissions, (ii) PPP, (iii) humus accumulation, and (iv) erosion. To avoid an overly long paper, we omit description of the other indicators (ammonia emissions, nitrate leaching, phosphorus leaching, biodiversity). For details of the simple system, see also Gilgen et al. (2022a).

3.1. Greenhouse gas emissions

3.1.1. Detailed system

The indicator for GHG emissions was derived through the following three steps: (i) identification of the most important GHG sources within the Swiss agriculture sector; (ii) selection of the major emission sources/sinks that contribute most to Swiss agricultural GHG emissions, based primarily on the Swiss national GHG inventory (FOEN 2021) and consolidated results of LCA studies (e.g., Alig et al. 2015); and (iii) derivation of a suitable and sufficiently accurate parameterization. Special focus was placed on animal husbandry, because it is responsible for approximately 85 % of GHG emissions from Swiss agriculture (Bretscher et al. 2018).

This analysis identified the five following major GHG sources: (i) methane (CH_4) emissions from ruminants by enteric fermentation (e_1), (ii) nitrous oxide (N_2O) emissions from agricultural soils (e_2), (iii) emissions from drained organic soils (e_3), (iv) carbon stored in trees (e_4), and (v) CH_4 and N_2O emissions from stored slurry (e_5). Together, these account for more than 90 % of Swiss GHG emissions, including agricultural emission sources allocated to land use change and traffic (FOAG

2019). Total GHG emissions in tons of carbon dioxide equivalents (CO_2-eq) per hectare are:

$$GHG_{complex} = \frac{e_1 + e_2 + e_3 + e_4 + e_5}{UAA}, \quad (1)$$

where the GHG sources e_1 to e_5 are expressed at farm level and in relation to the farm's utilized agricultural area (UAA). Division by UAA is necessary because direct payments are distributed per hectare. In the following, we briefly describe the parameterizations for emission sources/sinks e_1 to e_5.

Anthropogenic methane emissions from enteric fermentation (e_1).

Methane emissions from Swiss ruminants (i.e., cattle, sheep, goats, and other ruminants) amount to approximately 3 t CO_2-eq per livestock unit (LU) and year (FAO 2018; Münger et al. 2018), with dairy cows contributing approximately 80 % to total CH_4 emissions in Switzerland (Hiller et al. 2013; Bretscher and Ammann 2017). We ignored non-ruminant animal species (poultry, horses, pigs) because they only make a marginal contribution to total CH_4 emissions. We extended parameterization by the number of lactations from dairy cows (*lac*) for the following reasons: (i) dairy production is crucial for Swiss milk and meat production, (ii) lactating dairy cows contribute by far the most to the total CH_4 emissions, and (iii) GHG emissions with the product-related functional unit (per kilogram of meat or liter of milk) decrease markedly with increasing number of lactations (Schader et al. 2014; Alig et al. 2015; Zehetmaier et al. 2017). The latter aspect is related to the fact that dairy cows emit CH_4 from immediately after birth, while giving milk only from about two years of age. Based on the above considerations, we developed the following formula for CH_4 emissions from enteric fermentation by ruminants:

$$e_1 = c \cdot \left(\frac{2 \cdot lac + 2}{2 \cdot 1.286 \cdot lac}\right) \cdot LU_{dairy\ cow} + c \cdot LU_{other\ ruminants}, \quad (2)$$

where LU is livestock units, c is mean CO_2-eq emissions per ruminant LU (=3.0 t CO_2-eq/year), and *lac* is number of lactations. The factor 1.286 normalizes the value within brackets for the observed mean number of lactations in Switzerland ($lac = 3.5$). Farms with lactation numbers smaller/greater than 3.5 thus achieve more/less than 3 t CO_2-eq/year per dairy cow.

Nitrous oxide emissions from agricultural soils (e_2).

Nitrous oxide (N_2O) is the third most important of the long-lived GHG in terms of its contribution to global warming, because its global warming potential (GWP) is 265 times that of CO_2 over a 100-year timescale (IPCC 2013). The agriculture sector is responsible for about 87.2 % of N_2O emissions, mainly originating from animal waste management and agricultural soils (Signor and Cerri 2013). The N_2O emissions from agricultural soils can be divided into direct emissions and indirect emissions. Sources of indirect emissions of N_2O are re-deposition of reactive nitrogen compounds such as ammonia and nitrogen oxides on nearby soils, nitrate leaching, and runoff (Nevison 2002). Ammonia emissions and nitrate leaching were ignored, because these processes are considered in other indicators of the IBDP system. The most important sources of N_2O emissions from soils are applied manure (slurry and manure), mineral fertilizers, and excretion by animals on pastures (FOEN 2021). Based on this information, which complies with the Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 2006; IPCC, 2019), the following parameterization was derived:

$$e_2 = r \cdot \left[EF_N \cdot N_{fert} + \sum_{a=1}^{m} \frac{d_{graz}}{365} \cdot \frac{h_{graz}}{24} \cdot EF_{past} \cdot N_{excr}\right], \quad (3)$$

where $r = 0.416$ is the product from the GWP of N_2O ($GWP_{N2O} = 265$), the conversion factor of N_2O-nitrogen (N_2O-N) to nitrogen (N) based on molar mass (=1.57), and the conversion from kilograms to ton (=0.001). N_{fert} is the mass (in kilograms) of N through applied manure or fertilizer and recycled manure, and N_{excr} is the annual average N excretion for each livestock species (in kilograms) (typical N_{excr} values per head for all relevant animal categories can be found in Richner et al. (2017)). EF_N (=0.01 N_2O-N/kg N) is the emission factor (EF) for applied manure or fertilizers and EF_{past} is the EF for animal excretion on pastures. For cattle, poultry, and pigs, an value of $EF_{past} = 0.02$ kg N_2O-N/kg N was assumed, and for sheep and goats a value of $EF_{past} = 0.01$ N_2O-N/kg N (FOEN 2021). The sum in the second term in Eq. (3) runs over all m animal categories given in Richner et al. (2017). The product of the two terms containing d_{graz} (number of grazing days) and h_{graz} (number of grazing hours per day) represents the fraction of time spent grazing on pasture.

Carbon dioxide emissions from organic soils (e_3).

Undisturbed peatlands with typically high watertables usually act as long-term soil carbon sinks, whereas drained peatlands emit large amounts of CO_2 because of aeration and enhanced mineralization (Leifeld and Menichetti 2018). Carbon dioxide dominates GHG emissions from organic soils (~90 % of the total) (Tiemeyer et al. 2020). Therefore, we ignored the typically greatly varying contribution from CH_4 and N_2O. Based on Tiemeyer et al. (2020), we described the emissions from field i with area $a_{i,org}$ depending on the mean annual watertable depth d_{water} (given in distance beneath the Earth's surface) with the following formula):

$$e_3 = a_{i,org} \cdot \left[\sum_{i=1}^{p} e_{org40} \cdot (d_{water} - k)\right], \quad d_{water} = [10\ cm, 40\ cm], \quad (4)$$

where $e_{org40} = 1$ t CO_2-eq/ha and $k = 10$ cm. If d_{water} is outside the interval [10 cm, 40 cm], the value is set back to the respective closer threshold. Evaluating the formula for watertables beyond 40 cm soil depth leads to emissions of 30 t CO_2-eq/ha, while CO_2 emissions from wet soils ($d_{water} < 10$ cm) are set to zero. If data acquisition on watertable depth is not feasible, we suggest selecting standard EF for drained organic soils from the temperate zone, since a review by Paul and Alewell (2018) concluded that overly complex parameterizations cannot be justified because confidence intervals of different types of organic soils (for both grassland and crop) remain considerable.

Carbon storage in trees (e_4).

Planting trees on agricultural land is an effective way to capture carbon, leading to negative emissions (Lewis et al. 2019). We considered (i) trees that contribute to food supply (e.g., high-stem fruit trees), (ii) other (long-term) trees stands, and (iii) agroforestry systems. Assuming that one tree captures approximately 0.02–0.03 t carbon per year (AGRIDEA 2019), together with the ratio of molecular weight of CO_2 to that of carbon (44/12 = 3.67), we roughly obtained for n trees (n_{tree}) the following storage capacity:

$$e_4 = -0.1\ t\ CO_2eq \cdot n_{tree}, \quad (5)$$

This approximation is in line with more elaborate estimates using allometric equations for above-ground biomass of typical tree species cultivated in Switzerland (Price et al. 2017).

Storage of farmyard manure (e_5).

Storage of farm manure leads to ammonia, CH_4, and N_2O emissions. To avoid double counting, we ignored ammonia and indirect N_2O emissions because they are considered in the ammonia indicator (Gilgen et al. 2022b). We restricted the parameterization to slurry storage, because emissions from liquid manure are far higher than those from solid manure. Following Kupper et al. (2020), we assumed emissions from an uncovered liquid manure tank of $EF_{N2O} = 0.002$ g/(m^2·h) and $EF_{CH4} = 0.6$ g/(m^3·h). Most storage tanks are covered in Switzerland. Therefore, we reduced the factor EF_{CH4} by 20 %; for N_2O, the few available records do not show a statistically significant reduction of N_2O emissions (Kupper et al. 2020). Conversion of units from grams to tons, together with GWP of 265 for N_2O and 28 for CH_4, resulted in the following approximation for the GHG emitted from a slurry tank of area a_{tank} and with mean undiluted slurry volume v_{slurry}:

$$e_5 = k_1 \cdot a_{tank} + k_2 \cdot v_{slurry}, \tag{6}$$

where $k_1 = 0.00464$ t CO_2-eq/m^2 and $k_2 = 0.118$ t CO_2-eq/m^3.

3.1.2. Medium system

The GHG emissions indicator in the indicator system with medium complexity closely followed the method applied in the complex system, but in a simplified form. Emissions from stored manure (term e_5, Eq. (6)) were neglected because these contribute comparatively less to GHG emissions and the reduction potential in Switzerland is low (apart from the reduction in livestock numbers). The first four emission terms (e_1 to e_4 in Eq. (1)) were simplified as follows: (i) number of lactations of dairy cows was ignored in term e_1, (ii) N_2O emissions from excretion by livestock on pasture were omitted in term e_2, and (iii) the dependence of CO_2 emissions from organic soils on watertable depth was ignored in term e_3. For the latter, a mean $EF_{org} = 30$ t CO_2-eq/ha for organic arable land with area $a_{crop,org}$ was assumed (Paul and Alewell 2018). These simplifications led to the following parameterization for the GHG emissions GHG_{med}:

$$GHG_{med} = \frac{c \cdot LU_{rum} + r \cdot EF_N \cdot N_{fert} + a_{crop,\ org} \cdot EF_{org} - 0.1\ t\ CO_2eq \cdot n_{tree}}{UAA}, \tag{7}$$

where c represents the mean GHG emissions (mainly CH_4) per LU (=3 t CO_2-eq/year), and LU_{rum} is the total LU of all ruminants (dairy, sheep, goat, and other ruminants).

3.1.3. Simple system

In the simple system, we did not include an indicator to exclusively describe GHG emissions. Instead, we devised an indicator $GHG\_am\_nitr_{simple}$ for the combined effect of GHG emissions, ammonia emissions, and nutrient leaching, by a linear function of LU per hectare and total applied N (Eq. (8)). The number and type of livestock has a strong influence on GHG emissions and ammonia emissions, whereas the total applied *N*-fertilizer largely influences N_2O and ammonia field emissions, as well as nitrate leaching. In contrast to the indicator in the other two IBDP systems, the units of this indicator were given in the interval [0,1] instead of CO_2-eq (Eq. (8)):

$$GHG\_am\_nitr_{simple} = 1 - \left(k_1 \cdot LU/ha\ + k_2 \cdot N_{fert}/ha\right), \tag{8}$$

where LU represents the number of LU and N_{fert} the amount of applied *N*-fertilizers (in kilograms of N per hectare). Both variables were given at the farm level. While in principle adjustable, parameters k_1 and k_2 were set to $k_1 = 0.33$ and $k_2 = 0.0025$. $GHG\_am\_nitr_{simple}$ directly determined the magnitude of the negative impact due to *N*-fertilization and livestock density. In order to keep the formula very simple, we refrained from discriminating between granivores and ruminants. Farms with no livestock and no application of *N*-fertilizers were assigned an indicator value of 1, meaning that they were operating optimally in environmental terms.

3.2. Application of plant protection products

3.2.1. Detailed system

Plant protection products play a crucial role in reducing yield losses due to pests and diseases (Savary et al. 2019). The disadvantage of PPP is that they can have negative impacts on biodiversity and human health (Mathis et al. 2022). The potential of negative PPP impacts was assessed in the complex IBDP system by risk scores developed by Korkaric et al. (2020). These risk scores of authorized PPP allow ranking of the risk potential of active substances, but they do not allow estimation of the effective risk because they do not include any risk measures taken by the farmer. Korkaric et al. (2020) suggested separate risk scores for groundwater, surface waters, and bees, so effects of PPP application on human health would be excluded. This distinction is required because the effect of PPP often varies greatly for different species and categories. In the detailed IBDP system, we built a scoring system based on these risk scores. This was achieved by the following two steps: First, we normalized the risk score for each active substance i by using the mean application rate (MAR) in grams per hectare, as used in Korkaric et al. (2020) for the risk score (RS) estimates:

$$RS_{i,\ norm} = AR_{i,farm} \cdot \frac{RS_i}{MAR_i}, \tag{9}$$

where $AR_{i,farm}$ represents the total applied amount of the active substance i divided by the UAA in units g/ha.

We then converted $RS_{i,norm}$ to a number S_i within the interval [0,10]. To account for the fact that the risk scores differ in magnitude, we calculated their square root (Eq. (10)). This approach avoids having the most toxic active ingredient contributing (almost) exclusively to the final score.

$$S_i = \sqrt{RS_{i,norm}} \cdot \frac{10}{\sqrt{RS_{i,\max}}}, \tag{10}$$

where $RS_{i,\max}$ represents the risk score of the most toxic active substance applied on the farm.

The calculations in Eq. (9) and Eq. (10) were performed for each applied active substance i and for each of the three categories groundwater (*gw*), surface waters (*sw*), and bees (*b*). Finally, the scores S_i were added up for each category separately and then added again over the three categories (Eq. (11)):

$$S_{tot} = \sum_{i=1}^{p} S_{i,gw} + \sum_{i=1}^{p} S_{i,sw} + \sum_{i=1}^{p} S_{i,b}, \tag{11}$$

where S_{tot} is the final score specifying the overall toxic potential of all p active substances applied on the farm. The value of S_{tot} then directly increases the payment to the farmer (see Gilgen et al. 2022a). Direct inclusion of emission-reducing measures in the scoring system is difficult. Therefore, we propose prescribing application techniques that reduce drift and wash-off by at least 75 %.

3.2.2. Medium system

We reduced the complexity of the PPP indicator in the medium system by merely considering the most toxic substances given in Korkaric et al. (2020), but without taking into account the specific risk score of the active substances. This list currently includes 17 substances (mostly herbicides) for groundwater, 15 (mostly insecticides) for surface waters, and five insecticides for bees. Accordingly, the farm's PPP risk due to the applied p active substances was reduced to a simple equation (Eq. (12), with Eq. (13)):

$$S_{tot} = \sum_{i=1}^{p} A_{i,norm} \cdot a_i, \tag{12}$$

where a_i is the fraction of the farm's UAA on which the active substance i is applied, and

$$A_{i,norm} = \frac{AR_{i,farm}}{MAR_i}, \tag{13}$$

with abbreviations given in Eq. (9).

Note that the list of the most toxic active substances is subject to constant change, as PPP with high damage potential will increasingly be forbidden in European agriculture. It is thus crucial to update the list with the most toxic substances regularly if the environmental goals have not yet been achieved.

3.2.3. Simple system

For the simple system, we propose a binary variable distinguishing between the cases where the farmer applies/does not apply any active substance on the list of very toxic substances according to Korkaric et al. (2020).

3.3. Soil organic matter (humus)

3.3.1. Detailed system

Gradual decomposition of dead soil organic matter from plant roots, crop residues, and organic fertilizers results in formation of more complex organic matter called humus, comprising the resistant and stable part of soil organic carbon (SOC) (Juma 1998). SOC affects many soil properties and is one of the most important determinants of the fertility of mineral soils. Soils with high SOC content can store more nutrients and water, and allow better uptake of nutrients by plants. The SOC content is correlated to a number of soil physical properties, such as soil bulk volume, moisture retention curve, fluid transfer properties, and mechanical resistance of the soil to stresses (Johannes et al. 2017). Therefore, SOC can be considered a very suitable parameter to describe soil physical properties. Swiss regulations require regular measurement of SOC on farms for cross-compliance purposes, so it is reasonable to use this indicator of soil quality within the detailed IBDP system. The mandatory SOC field surveys performed every 10 years allow variations in SOC content at plot level to be considered. Note that visual inspection is not sufficient for our purposes. Rather (several) laboratory samples have to be drawn on each plot in order to guarantee required accuracy and consider the spatial variability in humus content.

When classifying the structural soil quality of mineral soils (we excluded organic soils), it is crucial to note that with increasing clay content, higher SOC content is required to achieve the same level of aggregate stability (Johannes et al. 2017). The reason is that in most soils, a significant percentage of SOC is typically bound to clay minerals. A higher clay content delays humus decomposition because the humus constituents are more strongly bound or trapped by the clay particles (clay-humus complexes). Based on findings by Johannes et al. (2017), we derived a normalized humus indicator I_{hum} that can be considered as an impact indicator whose value directly determines the payments for the farmer. With some slight adaptions and based on recent expert knowledge, we constructed the humus indicator as a piecewise linear function with x = SOC:clay (both values given in percentages per weight) as follows:

$$I_{hum} = \begin{cases} 0, & \text{if } x < \frac{1}{18} \\ 9 \cdot x - 0.5, & \text{if } \frac{1}{18} \leqslant x < 1/6, \\ -6 \cdot x + 2, & \text{if } \frac{1}{6} \leqslant x \leqslant 1/4. \end{cases} \tag{14}$$

The shape of the function for I_{hum} in Eq. (14) is closely associated with the relationship between soil quality and the SOC:clay ratio, as shown in Fig. 1.

Following Eq. (14), we propose a SOC:clay ratio = 1/8 as an optimum for good soil structure quality (i.e., $I_{hum} = 1$), with I_{hum} decreasing linearly to $I_{hum} = 0.5$ at SOC:clay = 1/4 and to $I_{hum} = 0$ (very poor soil structure quality) at SOC:clay = 1/18. Values beyond SOC:clay = 1/4 are not classified by such ratios because these values are more typical for organic soils than for mineral soils. The non-symmetric shape of the piecewise linear function can be justified by the fact that very low humus content harms soils more than excessive humus content. Soils with SOC:clay <1/18 can be considered very poor soils whose structure is likely degraded.

3.3.2. Medium system

For the humus indicator in the system of medium complexity, we followed the catalogue of measures enhancing humus accumulation developed as an action plan ("Humus Resource Programme") for the Swiss canton Solothurn (Solothurn 2019). This action plan promotes the use of humus-enhancing measures through financial incentives. The following measures were considered: (i) availability of annual humus balance calculations [yes/no], (ii) manure composting [amount in tons], (iii) green manure [area in hectares], (iv) forage rye, (v) cover crops [area in hectares], (vi) temporary grassland with alfalfa [area in hectares], (vii) permanent grassland, and (viii) continuous ground cover on arable land [yes/no]. These measures are effective ways for farmers to enhance and stabilize their soil humus content, while simultaneously

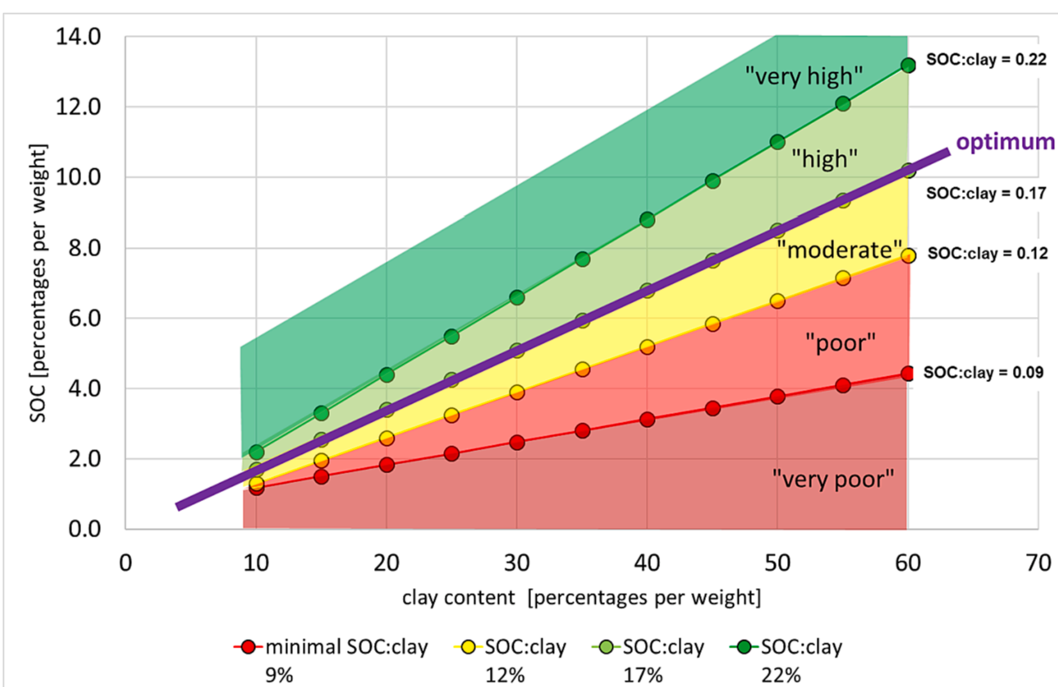

Fig. 1. Soil status as a function of soil organic carbon (SOC):clay ratio. Slightly adapted from Johannes et al. (2017).

allowing a high degree of flexibility. To normalize the humus indicator, the incentives suggested in Solothurn (2019) for the measures listed above were linearly converted into scores (see Table 1), followed by adding all points and dividing by total UAA. Yes-no questions were allocated 1 point for a positive answer and zero otherwise (with the exception of continuous ground cover, which was allocated 3 points). Manure composting was allocated 0.2 points per ton of manure, again following the incentives suggested in Solothurn (2019).

The humus balance calculations were performed using the approach developed at Agroscope, i.e., by subtracting humus decomposition from humus-forming organic matter according to the method of Neyroud et al. (1997).

3.3.3. Simple system

No humus indicator was developed for the simple system. Instead, we merged the humus and erosion indicators to create a simple soil indicator (see section 3.4.3).

3.4. Erosion

3.4.1. Detailed system

We considered it crucial to include soil erosion in the IBDP system, because erosion triggers land degradation, decreases effective root depth, and reduces production (Naipal et al. 2015). Panagos et al. (2015) identified soil erosion by water as the major threat to soils in the European Union. The revised universal soil loss equation (RUSLE) model is a suitable method for constructing an adequate erosion indicator, owing to its simple structure, empirical basis, wide global use, and high degree of validity (Renard et al. 1991). It predicts the long-term average and annual rate of erosion based on rainfall pattern, soil type, topography, crop system, and management practice. The RUSLE model can be expressed by the following equation for the annual soil loss I_{eros}:

$$I_{eros} = R \cdot K \cdot L \cdot S \cdot C \cdot P, \tag{15}$$

where I_{eros} is the average annual soil loss [kg/ha/yr], R is a rainfall erosivity factor [kJ/m^2/mmh^1/yr], K is a soil erodibility factor [kg/ha/(kJ/m^2/mmh)], L and S are slope length and slope steepness factors, respectively (dimensionless), C is a land management factor (dimensionless), and P is a conservation practice factor (dimensionless).

The factors R, K, L, and S in Eq. (15) depend only on climate (precipitation) and location (soil characteristics, length and steepness of the slope), i.e., they are independent of land use or crop management. The product of factors R, K, L, and S describes potential soil erosion loss. This information can be retrieved from the high-resolution erosion risk map (2×2 m) developed at Agroscope (Prasuhn et al. 2013), which categorizes soil loss risk into three levels (low, medium, and high potential erosion risk). These three risk levels were considered in Eq. (16) by a weighting factor $w_{RKLS} = 0$, 0.5, and 1.0 for low, medium and high risk, respectively. Farmers only receive payments for measures on erosion-prone land.

Table 1
Scores (in points) for measures enhancing humus accumulation.

Measure	Points (pt)
Calculation of humus balance	yes = 1pt, no = 0 pts
Manure composting	0.2 pts/ton compost
Green manure (early/late)	1pt/ha / 0.5 pts/ha
Forage rye	1pt/ha
Cover crops	0.5pt/ha
Temporary grassland with alfalfa or multiannual temporary grassland	1.75 pts/ha
Permanent grassland	1pt/ha
Continuous ground cover on entire arable land	3 pts/farm
Organic arable land*	−1pt/ha

* Deduction for organic arable land added considering that organic soils are subject to high humus losses, and thus high CO_2 emissions (Tiemeyer et al., 2016).

Factor P in Eq. (15) characterizes soil loss changes related to specific support practices such as contour farming or stone walls (Renard 1997). Because this aspect was beyond the scope of the IBDP system, we set $P = 1$. The management factor C, a dynamic factor that depends on the amount and type of vegetation cover, can be modified by the farmer in the short term through land management. However, detailed assessment of factor C is quite complex. Thus, the effect of management was considered in a simplified manner based on a detailed description of crop rotation characteristics by Mosimann and Rüttimann (2006). Accordingly, we derived an expression for the annual soil loss on the cr farm's crop plots of area a_i, total cropland area $a_{crop,tot}$ and total grassland area $a_{grass,tot}$ (Eq. (16)). The higher $I_{eros,arab}$, the higher the annual soil loss:

$$I_{eros,arab} = \frac{1}{a_{crop,tot} + a_{grass,tot}} \sum_{i=1}^{cr} a_i \cdot w_{RKLS} \cdot w_e \cdot \left[B_{tg} + B_{rc} + f_{wf} + f_p\right], \tag{16}$$

where B_{tg} and B_{rc} are binary variables depending on specific thresholds for the fraction of area in the crop rotation of temporary grassland (tg) and root crops (rc): B_{tg} is set to 1 if the fraction of temporary grassland in the crop rotation is above 30 %, and 0 otherwise; B_{rc} is set to 1 if the fraction of root crops (maize, potatoes, and sugar beet) in the crop rotation is below 50 %, and 0 otherwise (Schwertmann et al., 1987). The fraction f_{wf} stands for the relative frequency of crop rotations without winter fallow, and f_p is the relative frequency of no-till crops within the crop rotation. The physical process underlying the two parameters f_{wf} and f_p is that winter fallow is prone to enhanced erosion, whereas no-till reduces the risk of eroded soil. Conventional tillage produces a smooth surface that leaves soil vulnerable to erosion (Chalise et al. 2019). The four terms in square brackets in Eq. (16) are equally weighted, i.e., $w_e = 0.25$.

Permanent grassland is generally subject to low levels of erosion, thus resulting in small amounts of eroded soil (Milazzo et al. 2022). Therefore, we assumed for permanent grassland:

$$I_{eros,grass} = \frac{1}{a_{crop,tot} + a_{grass,tot}} \sum_{i=1}^{p} a_i, \tag{17}$$

with the sum running over all p plots with permanent grassland of area a_i. The total average annual soil erosion $I_{eros,tot}$ at the farm level is given by:

$$I_{eros,tot} = I_{eros,arab} + I_{eros,grass}, \tag{18}$$

where the design of $I_{eros,tot}$ ensures normalized values within the interval [0,1], with rising values related to decreased soil erosion.

3.4.2. Medium system

In the detailed system, calculation of the erosion indicator required information on relative frequencies in the crop rotation. This required data on cultivated crops over several years, complicating computation and verification. Therefore, we propose an indicator that focuses on the most important factors for erosion, while omitting details of the actual crop rotation, but this indicator is so far only conceptual. Therefore, we suggest the following two-step procedure: i) assign each crop to an erosion risk score, and ii) add a correction term depending on intercropping and tillage (e.g., reduce the score when ploughing is carried out). Data from the Swiss Agri-Environmental Data Network could be used to compute the C values for different crops.

3.4.3. Simple system

To account for the key drivers of soil erosion related to farm management in the simple system, we suggest linking the direct payments to the total area of (i) temporary grassland, (ii) ley, and (iii) catch crops, reduced by the area of root crops (maize, potatoes, and sugar beet). This simple approach is based on the fact that cultivating grassland, ley, or catch crops has a positive effect in terms of erosion reduction and humus accumulation, whereas root crops are prone to enhanced soil erosion and a decrease in humus content.

4. Discussion

The IBDP system is a novel indicator system aiming at replacing (with a few exceptions such as biodiversity; see Gilgen et al. 2022b) environment-related direct payments in the current system. In most cases, the indicators do not contain a number of single, independent measures, but rather aim at a feasible description of the most relevant driving physical processes. Most indicators focus on agricultural structures and measures (e.g., size of herd, avoided use of high-risk PPPs) and only a few are results-based or at least contain results-based components (e.g. measurement of humus content).

The main challenge was to create a customized design where the indicators are in line with policy-driven constraints regarding the data (with respect to time and validity), while not ignoring a sufficient level of informative value. This challenge was recognized by Radermacher (2021), who stated that the main characteristic of indicators is their purpose and the context of interpretation. All IBDP indicators, excluding GHG emissions and PPP, are normalized within the range 0 to 1, with increasing values related to decreasing negative impact of the environmental dimension considered. The indicators capture the potential impact per hectare of UAA. Normalized indicators simplify translation from value of the indicator into a payment level. For illustration, Fig. 2 shows how the value of the indicator for GHG emissions is converted into a direct payment amount, assuming a linear relationship between two threshold values of the indicator and the level of direct payments. Based on Fig. 2, we suggest a linear reduction in payments between a maximum level of 1140 CHF/ha/yr for zero GHG emissions and no payment for GHG emissions above 6 t CO_2-eq/ha/yr.

Because all indicators are quantitative and are based on (generally) easily gathered input data, they can be considered valid. Their verifiability should also be good, because farmers' options to submit incorrect data are minimal as all input data can be verified and checked by independent control organs, with very few exceptions of subjective ratings (e.g., grazing duration, use of plough). The proposed indicators are reliable because the value (and thus the conclusion reached) remains the same if measured by different people at different times. The design of the IBDP system, including its three systems with different complexity levels, makes it feasible and flexible, allowing users to optimize trade-offs between accuracy and completeness and the time requirements for data acquisition.

The indicators developed for the detailed system aim at covering the most important physical processes driving the environmental impacts. However, policy-given constraints do not allow all processes to be covered in detail, since complex physical process-oriented models are not suitable for our purposes.

The following sections provide a detailed assessment of the IBDP system, based on stakeholder feedback gathered during a one-day workshop and preceding discussion rounds in oral and written form. The 15 participants came from different departments of the Swiss Federal Office for Agriculture, cantonal agricultural agencies, agricultural extension services, and the agri-environmental sector. The focus in discussions was on: (i) general assessment of the IBDP systems of three different complexity levels, (ii) advantages and disadvantages of the three IBDP systems, and (iii) implementation of the IBDP system, including challenges and approaches for practical realization.

4.1. General assessment of the IBDP system

Workshop participants of the workshop rated the IBDP system very highly, for three main reasons:

(i) Direct payments that are directly linked to environmental damage provide potential to reduce negative environmental impacts caused by agricultural production. The current system for direct payments largely lacks this feature, preventing achievement of AEO goals.
(ii) The IBDP system can help to overcome the current complex regulation for direct payments (most experts agreed with this statement).
(iii) The novel system helps to increase the farmer's self-responsibility and simultaneously increases transparency through a common framework that is identical for all environmental impacts. This is especially true for the detailed IBDP system, which provides greater flexibility in adapting management practices towards lowering the environmental footprint of the agriculture sector.

In implementation, the challenge is to find the optimal compromise between targeted improvements and the administrative burden for the

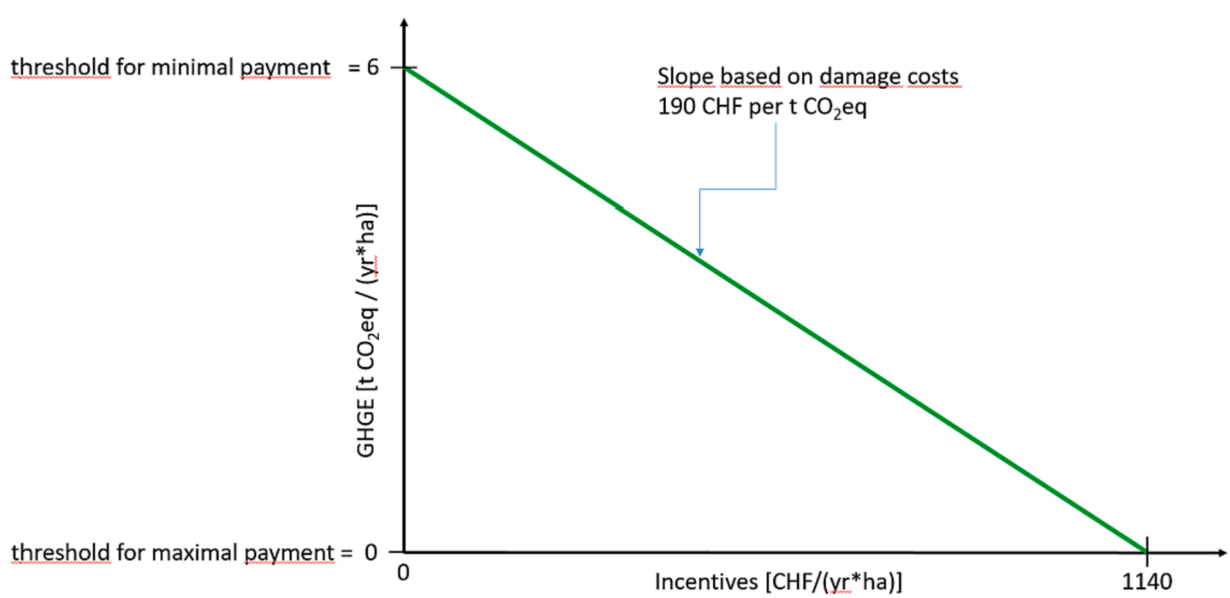

Fig. 2. Illustration of conversion from greenhouse gas (GHG) emissions to direct payment amount between two thresholds, assuming a linear relationship. Slope based on damage costs (Gilgen et al. 2022a).

farmer and agricultural agencies. A basic prerequisite for acceptance, and thus for successful implementation, is the communicability of the indicators concerning both the (physical) foundation and the meaning of different terms and their calculation. Future implementation will require thorough verification of possible conflicts with the current direct payment system. Some of the experts at the workshop pointed out possible trade-offs between reduced environmental impacts and reduced food production, particularly for the simple IBDP system because it does not respond to management measures, although the low administrative burden has a favorable effect. The detailed system suffers from increased time efforts for data acquisition, but the trade-off between reduced environmental impacts and reduced food production is reduced because the farmer can take various measures to reduce negative environmental impacts.

The stakeholders expressed differing opinions on the IBDP system's effectiveness in reducing negative environmental impacts. Concerns primarily related to the influence of impacting factors outside the direct payment system, such as market support measures (e.g., the relevance of border protection for agricultural products and other existing systemic structures). This may lead to high opportunity costs for farmers, at least in the short and medium term. In addition, there was consensus among the experts that a system focusing on individual farms may not necessarily lead to the desired outcomes formulated in the AEOs, which are defined at larger scales (supra-regional and national). Instead, it was suggested that an entire region (e.g., catchment area) should meet an environmental target in order for all farms in that region to receive direct payments.

Finally, it is crucial to test the novel IBDP indicators on a sufficiently large sample to verify their usefulness, feasibility, and acceptance under real-life conditions.

4.2. Advantages and disadvantages of the three IBDP systems

Each of the three IBDP systems has its individual advantages and disadvantages. For this reason, the stakeholders suggested combining certain aspects of the three systems to optimize and maximize the benefits from a system change. It might also prove ideal to start with the simple IBDP system and later extend the system with selected components, possibly on a voluntary basis. However, it may be critical to implement the simple system as mandatory for receiving direct payments, while leaving additional aspects of the detailed system on a voluntary basis. These concerns derived from a questionable cost-effectiveness ratio due to a significant additional administrative effort for implementation of the detailed indicator system. Table 2 summarizes the main advantages and disadvantages of the three IBDP systems as identified by the stakeholders. The evaluation and rating of all information given in Table 2 suggests that the advantages of the three systems of different complexity levels could be combined to profit from positive features associated with the individual systems.

Table 2
Main advantages and disadvantages of the three indicator-based direct payments (IBDP) systems of different complexity. All statements are based on expert judgment during a one-day workshop and preceding written and oral exchanges.

	Advantages	Disadvantages
Simple system	• Easy to implement starting from the current system • Based on a few simple key input parameters (such as LU) directly driving the emissions • Low (or even negligible) time load for collecting input data and practical implementation • Few efforts for federal agencies	• Indicators poorly represent the underlying driving processes • Insufficient representation of the complex interrelationships between certain environmental impacts • Lack of flexibility • Farmers have only a few options and levers for reducing their farm's environmental impact • The potential for reducing negative environmental impacts may be low • Does not consider any technical measures, so indicator values linked to lower environmental burden may lead to reduced agricultural production
Medium system	• Represents a suitable compromise between the simple and detailed system for selected environmental impacts (e.g., soil)	• Combines the negative aspects of the simple and detailed systems for some environmental topics • The overall potential for reduced environmental impact may be similar to that of the simple system, but with a higher administrative effort
Detailed system	• Closer relationship between indicator value and environmental impact • Flexibility in taking measures to reduce negative environmental impacts • Simple implementation if input data are complete and available in sufficient accuracy • Good compromise between feasibility and impact • Great potential to strongly profit from improved data availability through digitalization • The farmer may also profit from autonomous additional data acquisition	• Complete implementation is a major challenge • Time-demanding acquisition of accurate and complete input data • Could create anxieties that the system will be even more complicated than the present system • Participation requires a lot of know-how • Timely communication of achieved results to the farmer may be critical (e.g., humus indicator)

4.3. Challenges and approaches for practical implementation

Thus implementation of the new IBDP systems is a very challenging task, particularly for the detailed system owing to its associated high administrative burden. Implementation of the simple system would benefit from low administrative effort, but that advantage might be outweighed by limited acceptance due to low flexibility because technical measures for reducing negative environmental impacts are not included. Table 3 provides a summary of the main challenges of a system change, together with possible solutions to overcome these challenges.

The information provided in Table 2 and Table 3 shows that practical implementation of the IBDP system has promising elements for improving the current Swiss agri-environmental direct payment schemes, while also posing a number of challenges. It is thus crucial to have all stakeholders, especially farmers and agricultural agencies and advisors, on board. To provide enough time for all participants to become familiar with the IBDP system, a targeted and stepwise approach should be taken. A fundamental aspect is for stakeholders to recognize that active participation can prevent excessive negative environmental damage.

4.4. Regionalization

In-depth discussions with experts revealed that the applicability of the IBDP system may also depend on the environmental issue. An assessment of environmental indicators at farm level was judged to be more suitable for impacts acting on local and small-scale level, e.g., application of PPP, soil quality, and biodiversity (without connection of protected areas). Other issues, e.g., nitrate and phosphorus leaching, require a more regional approach because these cannot be solved at the single farm level. Therefore, it is important to consider how and at which scale regional aspects could be incorporated into the IBDP system to further enhance its benefits. Regionalization of the IBDP system has the potential to solve environmental problems at regional level. Such an approach may also face major challenges due to knowledge gaps and lack of data. In addition, adjacent farms situated inside and outside a

Table 3
Main challenges to practical implementation of the indicator-based direct payments (IBDP) system and possible entry points to solutions.

Challenges	Possible solutions
• Implementation requires further developments and convincing proof that the farm's negative environmental impacts can be reduced distinctly	• Launch a pilot project, possibly with a reduced set of indicators
• The IBDP system probably does not allow achievement of politically set environmental targets	• Identify other relevant levers that might reduce the farm's environmental impacts. • Reduce existing contradictions in the current agricultural policy support system
• High complexity of the IBDP system limits acceptance and understanding and thus participation by farmers. • Transfer of responsibility to the farmer	• Communicate the benefits • Foster direct stakeholder involvement in future developments • Promote awareness and knowledge of environmental issues among farmers • Support farmers through education, training, and advisory services • Ensure support during the implementation phase
• Compatibility of current system and the IDBP system may be critical: Potentially opposing incentives • Compatibility with earlier investments may be critical	• Critically verify possible overlaps and contradictory incentives between the current policy and the IBDB system • Step-by-step progressive introduction (start with a selected subset of indicators) • Allow farmers to profit from a transitional period during which participation is voluntary • Consider the specific situation of the farmer (age, investments, education, etc.) as a basis for acceptance and participation.
• Data acquisition is time-consuming for farmers	• Simplify data acquisition, plausibility checks and transmission by exploiting developments in the field of digital technologies. • Establish working groups and platforms that enable intensive exchange related to the IBDP system

defined region may be treated unfairly, which could pose significant challenges.

4.5. International applicability

The proposed framework is valid outside Switzerland, since the underlying approaches follow general physical principles. However, the parameterizations and acquisition of necessary input data are generally country-specific. For example, we restricted our analysis to the most important agricultural sources in Switzerland when deriving the GHG indicator, but in other countries the most important drivers could be significantly different. We also used risk scores calculated by Korkaric et al. (2020) for PPPs used in Switzerland, but other countries may have different approved active substances and calculation of additional risk scores might be necessary. There are also problems of transferability to other countries growing crops not cultivated in Switzerland, such as tropical crops and fruits.

5. Conclusions and outlook

Work within the IBDP project demonstrated that it is not feasible to apply existing indicator-based systems or to use LCIA midpoints for promoting environmentally friendly agriculture within a direct payment system. Instead, revised indicators need to be developed for relevant environmental impacts that consider and incorporate the key drivers, taking into account various constraints related to the policy context. These constraints include time and financial restrictions in data acquisition and in computation of indicators. In addition, the required input data must not be open to falsification and manipulation. These constraints should largely be overcome by the novel IBDP system because no qualitative data are used in computation of the individual indicators.

There are no indicators that can optimally fulfil all expectations for a direct payment system simultaneously. For this reason, three systems of different complexity (simple, medium, detailed), which give greater weight to different objectives, were developed. Based on expert judgment and literature reviews, it is possible to construct indicators for relevant environmental impacts that provide sufficient completeness and accuracy, and simultaneously meet policy-imposed conditions. It should be noted, however, that even the detailed system represents only some environmental processes in detail and is thus far less complex than detailed scientific models. These simplifications are a prerequisite to ensure practical implementation in a political context.

Overall, the IBDP system is a promising approach for replacing the current direct payment system in a flexible and transparent manner, while contributing to achieving Switzerland's ambitious AEOs. However, it is crucial to refine and test the proposed system on a sufficiently large sample of farms, to gain more insights into the efficiency and practicability of the entire system at all levels of complexity. In addition, the extent to which the disbursed direct payments can be influenced by farmers must be evaluated carefully.

CRediT authorship contribution statement

Andreas Roesch: Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing. **Christian Flury:** Conceptualization. **Thomas Nemecek:** Writing – review & editing. **Stefan Mann:** Conceptualization, Supervision. **Christian Ritzel:** Writing – review & editing. **Anina Gilgen:** Conceptualization, Methodology, Writing – review & editing, Project administration.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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