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Using an expert system to assess biodiversity in life cycle assessment of vegetable crops

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ABSTRACT

Biodiversity loss in agricultural landscapes due to intensification of agriculture and degradation and loss of semi-natural habitats is a major issue that life cycle assessment (LCA) methods intend to address. No current LCA method is able to assess and compare impacts on the biodiversity of vegetable production systems as a function of farming practices and the local context. Based on a literature review and consultation with experts, the SALCA-BD expert system, originally designed to assess impacts on the biodiversity of cropland and grassland at field, rotation, and farm levels, was adapted to vegetable production systems. SALCA-BD is based on an inventory of the habitats found on a farm and a list of practices that can be implemented in these habitats. We distinguished an open field and a greenhouse as two distinct "level I" habitats, as a habitat's openness favours the exchange of species with surrounding habitats. These two habitats were subdivided into "level II" habitats that corresponded to vegetable crops. Given the many types of vegetables, we used a clustering method to create a few categories that grouped vegetables that had similar potential to host biodiversity. We created a category for intercropped vegetables for fields in which multiple vegetables are grown at the same time, which is common on microfarms. We tested the expert system at field and farm levels using scenarios and a farm case study. We quantified effects of changes to individual practices and practice intensities at the field level on biodiversity. The results highlighted the importance of semi-natural habitats for preserving biodiversity, in addition to low-intensity practices, which indicates that assessment at the farm level is more informative than that at the field level. Because it considers habitats and practices in detail, SALCA-BD is useful for assessing biodiversity at field and farm levels and for comparing farming systems with the same land use and type of management (organic or conventional), which other LCA methods for assessing biodiversity cannot do. Field size, which is a driver of biodiversity, is considered indirectly only when semi-natural habitats are included. As SALCA-BD does not consider impacts of the background system, combining SALCA-BD with comprehensive methods for assessing impacts on biodiversity is a promising perspective for more complete assessment.

1. Introduction

Life cycle assessment (LCA) is a method used worldwide to assess potential impacts of a product, or the system that produces it, on the environment (ISO, 2006). It allows comprehensive assessment to be performed, which can help compare the environmental profiles of products (Curran, 2014). It is based on a set of impact categories (e.g. climate change, eutrophication, ozone depletion) that cover a broad range of environmental issues. Negative impacts of human activities on biodiversity are recognised as a major environmental issue (IPBES, 2018). In particular, impacts of agriculture on biodiversity have been widely documented, especially due to the organisation of agricultural landscapes and the types and intensities of practices in and around fields (Abdi et al., 2021; FAO, 2019; Karp et al., 2012; Mupepele et al., 2021). Assessing impacts on biodiversity in LCAs of agricultural products is of primary importance (Koellner et al., 2013), and many studies have developed methods for doing so (Curran et al., 2016; Gabel et al., 2016).

Many of these methods are based on estimating impacts of land-use classes alone, with no consideration of land management. Koellner and Scholz (2008) and Mueller et al. (2014) developed characterisation factors (CFs) for impacts of conventional and organic farming systems on biodiversity within a given land-use class based on literature reviews

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of studies that used different sampling methods. Knudsen et al. (2017) developed CFs based on field data in Europe, including four agricultural land-use classes (i.e. monocotyledon pasture, mixed pasture, arable crops, and hedge) managed under conventional or organic practices. The method developed by Chaudhary et al. (2015), which provided CFs for 804 ecoregions and six land-use classes (i.e. intensive forestry, extensive forestry, annual crops, permanent crops, pasture, and urban) was provisionally recommended by the UNEP/SETAC Life Cycle Initiative (UNEP/SETAC, 2017) for analysing impact hotspots, but not for comparing systems. Chaudhary and Brooks (2018) updated the method by introducing three levels of land-use intensity: minimal, light, and intense. Hayashi (2020) compared impacts estimated by the updated method to field-level biodiversity (species richness) observations of rice production systems in Japan and found inconsistencies between regional- and field-scale species richness of plants and amphibians.

Because none of these methods can compare farms or fields that have the same land use and type of management (organic or conventional), two organic vegetable farms would have the same impact even though they may have practices (Pépin et al., 2021) that impact biodiversity differently. These methods are useful for identifying hotspots of impact on biodiversity but do not provide detailed analysis, particularly of agricultural systems whose farming practices and local characteristics must be considered (Teixeira et al., 2016).

The expert system SALCA-BD (Swiss Agricultural LCA—Biodiversity) (Jeanneret et al., 2014) integrates biodiversity into agricultural LCA as an independent impact category. It assigns coefficients to crop and non-crop habitats that reflect their ability to host terrestrial species diversity, and to farming practices that reflect their impact on biodiversity. The coefficients, combined with the practices selected by the user, result in scores for 11 indicator species groups (ISGs) (i.e. crop flora, grassland flora, birds, small mammals, amphibians, snails, spiders, carabid beetles, butterflies, wild bees, and grasshoppers), which can be aggregated to a single final biodiversity score at field, rotation, and farm levels. The method has been validated with field observations of plants and grasshoppers in grassland (Jeanneret et al., 2014) and of vascular plants, spiders, and wild bees in cropland, grassland, and semi-natural habitats (SNHs) (Lüscher et al., 2017). Unlike other methods that apply CFs based on land use, SALCA-BD focuses on agricultural systems and does not estimate an absolute value for species loss. It is valid for Switzerland and neighbouring regions. SALCA-BD's detailed analysis allows for comparison of fields or farms by considering the practices applied to crops and SNHs. It is useful for assessing farms and identifying and testing impacts of innovative alternatives (e.g. changes in practices or land use) on biodiversity. Because SALCA-BD is focused on on-farm activities (i.e. the foreground system), it does not consider off-farm activities (i.e. the background system), such as the production of imported feed or land occupied by the infrastructure used to transport inputs.

SALCA-BD, initially developed for cropland, grassland, and SNHs, was later adapted to orchards by Van der Meer et al. (2017). The aim of this study was to adapt SALCA-BD to vegetable crops, which had not been included in cropland, by adding habitats and practices specific to vegetable production systems (VPSs). VPSs differ from cropland by the presence of sheltered production in addition to open-field production and, on some farms, the practice of intercropping (i.e. growing two or more vegetables in the same field) (Pépin et al., 2021). To adapt SALCA-BD to VPSs, we first identified the habitats and practices specific to VPSs and estimated their impacts on biodiversity. We then performed sensitivity analyses of the main characteristics of VPSs at the field level. Finally, we applied SALCA-BD to a farm case study.

2. Materials and methods

2.1. The expert system SALCA-BD

SALCA-BD is based on an inventory of farming practices that may be applied to crops and SNHs (Fig. 1) and includes as many practices as possible that influence biodiversity on a farm (Jeanneret et al., 2014). The inventory lists "level I" habitats (e.g. cropland, grassland, SNHs), which are divided into "level II" habitats (e.g. winter wheat, unproductive pasture, hedgerows). For each habitat, farming practices (e.g. tillage type, tillage depth) are listed, and if needed, subdivided into up to three levels (i.e. I: plant protection, II: insecticide, and III: date of application).

Because habitats have different potentials for hosting each ISG (e.g. an onion field may be more favourable for crop flora than grassland flora), a coefficient ($C_{habitat}$) that expresses this potential that ranges from 0 (lowest) to 10 (highest) is assigned to each habitat. Similarly, because management practices may influence ISGs differently (e.g. tillage influences carabid beetles and birds differently), a coefficient ($C_{management}$) that expresses this influence that ranges from 0 (lowest) to 10 (highest) is assigned to each practice. Each farming practice has several management options that describe how the practice is implemented (e.g. for tillage type: "no tillage", "ploughing"). Based on an extensive literature review and expert consultations, the direct impact of each management option in a given habitat on populations of each of the 11 ISGs is rated (rating "R") on a scale from 0–5: 0 (not applicable), 1

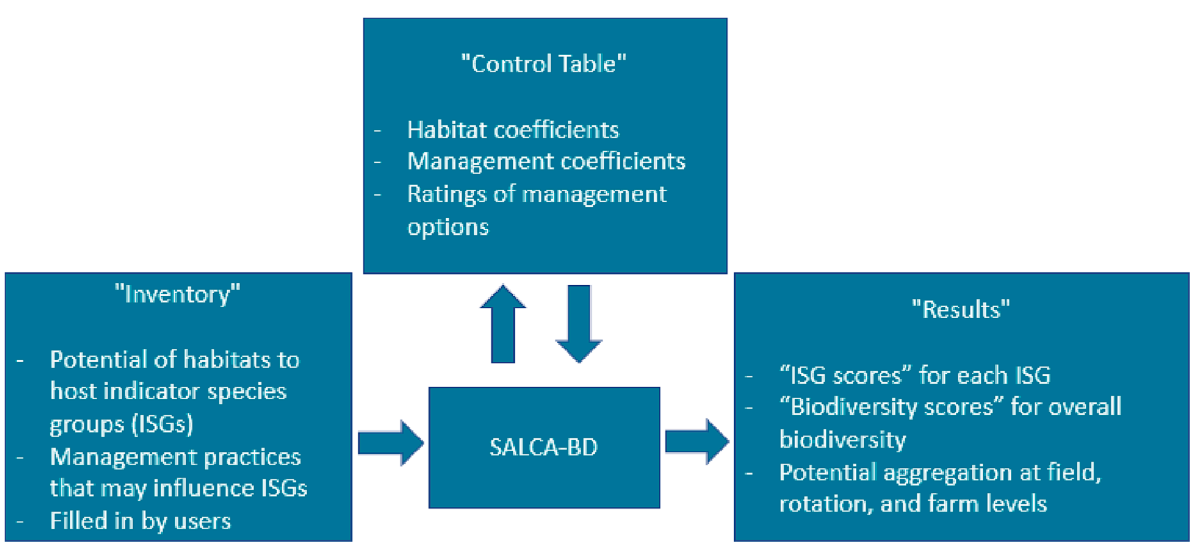

Fig. 1. The SALCA-BD framework. Users fill out the inventory file and import the control table into the expert system. The expert system assigns ratings and coefficients from the control table to the data in the inventory in order to calculate final scores.

(strong decline), 2 (decline), 3 (neutral), 4 (increase), and 5 (strong increase). For instance, the rating of herbicide applications for butterflies considers only mechanical and chemical impacts from direct contact, not indirect impacts due to removing potential host plants.

The final impact score of a practice implemented in a given habitat on a given ISG is calculated as $R \times (C_{habitat} + C_{management})/2$. The average of the impact scores of the practices in a given habitat on a given ISG equals the "ISG score" at the field level. A bonus or malus is applied to the "ISG score" at the field level to capture the influence of soil cover over a one-year period. The "ISG scores" for all 11 ISGs can be aggregated to calculate the impact on biodiversity (i.e. "biodiversity score") of a given habitat using weights that depend on the position of each ISG in the food web. Lower weights express a higher position of the ISG in the food web (i.e. consumes other ISGs). The biodiversity scores at the field level can be aggregated at rotation or farm levels using the areas of the fields as weights. The ratings and coefficients are listed in SALCA-BD's "control table".

2.2. Parametrisation of SALCA-BD to VPSs: The inventory and control table

Adapting SALCA-BD to VPSs required modifying the existing inventory and control table. The habitats, farming practices, and management options specific to VPSs were identified through a literature review, consultation with experts in VPSs (Supplementary Material 1), and statistical analysis. The literature review included studies from 1990 to 2020 in the temperate climate zone from scientific articles and grey literature, including magazine articles, trade-press articles, academic dissertations, institutional reports, book chapters, and conference proceedings (Mahood et al., 2014). The literature data bases used were the Web of Science, Google Scholar, and the online archives of FiBL (Forschungsinstitut für Biologischen Landbau), the Louis Bolk Insitute, and ITAB (Institut Technique en Agriculture Biologique). This step, which yielded 1132 records, took inspiration from a systematic review that parametrised SALCA-BD for orchards (van der Meer et al., 2020).

Level II habitats of cropland in SALCA-BD are crops (e.g. winter wheat, maize). Because VPSs contain many different crops, and little information about biodiversity is vegetable-specific, we defined level II habitats of VPSs as groups of vegetables that had similar potential to host all 11 ISGs. Starting with 40 vegetable crops (excluding perennials), we performed multiple component analysis (MCA), followed by agglomerative hierarchical clustering (AHC), to create a few categories. Each vegetable crop was described by four categorical variables that represented coarse habitat characteristics for biodiversity: height (low, medium, high), soil cover (low, medium, high), crop duration ($\leq$ 5 months, $>$ 5 months), and presence of flowers (yes, no) (Supplementary Material 2). The AHC was based on k-means consolidation of the Euclidian distance of the factorial coordinates of each crop, calculated using Ward's (1963) method. The optimal number of clusters was determined by considering the largest relative loss of inertia.

Once AHC had defined clusters, the relation between cluster number and the categorical variables was studied using a chi-square test. For each variable, a hypergeometric test was performed to characterise the clusters by their responses and to test whether each cluster over- or under-represented the responses. The MCA and AHC were performed using the R package FactoMineR (Lê et al., 2008), R software v. 3.5.3 (R Core Team, 2019), and RStudio v. 1.1.463 (RStudio Team, 2016).

Once the inventory had been created, we defined habitat coefficients, management coefficients, and ratings to build the control table. An initial version was based on findings of the literature review. This version was modified after interviewing experts of the ISGs, who were chosen because they were ecologists specialised in the ISGs, as recommended by Souza et al. (2015).

2.3. Sensitivity analysis

We conducted a one-at-a-time (OAT) sensitivity analysis to study the influence of farming practices and habitats on biodiversity scores at the field level. We analysed different management options of farming practices that were specific to VPSs for four contrasting vegetable categories (level II habitats) in each level I habitat, using wheat as a reference crop, as Jeanneret et al. (2014) did, for a total of 106 scenarios. Management practices that were not analysed in the sensitivity analysis were set to practices that are common on low-intensity organic farms (e.g. fresh manure and compost as fertilisers, low frequency of fertilisation). Biodiversity scores were calculated at the field level and aggregated for all 11 ISGs.

As a system-level sensitivity analysis, we compared two fields of onion cultivated with low- vs. high-intensity practices in each level I habitat that varied in fertilisation, weed control, pest control, and tillage. In the low- or high-intensity scenario, management options were the least or most, respectively, intensive in terms of frequency, quantity, and types of inputs. Biodiversity scores were calculated at the field level for each ISG and aggregated for all 11 ISGs.

2.4. Farm case study

We applied SALCA-BD to an organic vegetable farm in Brittany, France (geographic coordinates: 48°10′32.2″N 1°42′55.4″W), and calculated the farm-level biodiversity score using two boundaries: (1) cultivated areas only or (2) cultivated areas and SNHs. The farm produced vegetables and rye on 21 ha of open fields in a four-year rotation: potato/rye followed by turnip/cabbages (i.e. cauliflower, green cabbage, Savoy cabbage, Brussels sprouts, kale)/various vegetables (e.g. carrots, onions, squash). Fertilisation consisted of cow and poultry manure applied three out of every four years. Mechanical weeding was performed by tractor, and weeds in carrot crops were controlled by thermal weeding (flame produced using natural gas). Reusable anti-insect netting was used to cover certain vegetables, but there were few other types of pest or disease control. The farm was located in a hedgerow-network landscape. Its SNHs were 0.9 ha of extensive grassland, 2.6 ha of hedgerows around the fields, and 0.3 ha of ruderal area. The farm grew Jerusalem artichoke (*Helianthus tuberosu*, also known as topinambour or wild sunflower), which was not in the list of vegetables that we had used for the clustering; thus, we assigned to it the vegetable category whose characteristics were the most similar to its characteristics. The farm also grew potato, which exists in the original SALCA-BD as a level II habitat under cropland. Because this farm cultivated its potato more like a field crop (i.e. mechanised on large areas) than a vegetable, we assigned the expert system's pre-existing potato habitat to it.

3. Results

3.1. Parametrisation of the expert system SALCA-BD for VPSs

To cluster vegetable crops into level II habitats, two basic forms of vegetable production – an open field (OF) and a greenhouse (GH) – needed be distinguished as level I habitats because they differ in their openness and climate (i.e. temperature and humidity). Several types of GHs for vegetable production exist, but only those that could represent a habitat for any ISGs were considered. Soilless GHs were excluded as they are emptied and cleaned in winter, and can be considered as a building, which lies outside the scope of SALCA-BD. Only GHs with sides or ends that can be opened during the year, such as tunnels, bi-tunnels, and multi-span GHs, were considered.

Ultimately, we defined the same level II habitats for OF and GH (Table 1). The first three components of the MCA, which explained 74% of the variance, were retained for the AHC. Each variable was represented the most by one of the first three components. The AHC identified four clusters. Because vegetables that had the shorter duration and the

Table 1
Vegetable categories as a function of soil cover, height, crop duration, and presence of flowers. The characteristics of categories A-E were defined by agglomerative hierarchical clustering, and those in bold were significant (chi-square test: $p < 0.01$).

Category	Vegetables	Characteristics
A	shallot, fresh onion, onion, leek, garlic	• medium height • **low cover** • no flowers
B	head cabbage (e.g. Brussels sprouts, Savoy cabbage), leafy cabbage (e.g. kale), cauliflower, broccoli, other cabbage (e.g. Chinese cabbage), annual aromatic herbs	• low-medium height • **high cover** • no flowers
C	beetroot, Swiss chard, bunch radish, carrot, celery, celeriac, salad, mixed leaves, endive, fennel, lamb's lettuce, spinach, turnip, parsnip, radish	• low-medium height • **medium cover** • **no flowers**
D	eggplant, fava bean, pepper, potato, tomato, sweet potato	• **high height** • **longer duration** • **flowers**
E	pumpkin and squash, melon, watermelon, cucumber, courgette, bean, pea, early potato, edible flowers	• low-medium height • medium-high cover • **flowers**
F	artichoke	perennial, medium soil cover
G	asparagus	perennial, low soil cover
H	strawberry	perennial, flowers
I	intercropped vegetables	

presence of flowers were separated between two of them, we grouped these vegetables to create a fifth cluster. From the AHC, five categories of annual vegetable habitats that had similar characteristics were created (categories A to E). The chi-square tests indicated that all four categorical variables (i.e. height, soil cover, crop duration, and presence of flowers) were significantly ($p < 0.01$) related to the cluster number of each category. Category A was characterised by low soil cover and grouped vegetables in the Liliaceae family. Category B was characterised by high soil cover and grouped vegetables in the Brassicaceae family along with annual aromatic plants. Category C grouped leafy and root vegetables with medium soil cover, without flowers. Category D grouped tall plants with a longer duration and flowers, which were mainly vegetables in the Solanaceae family and fava bean, but not early potato, which was grouped in category E. Category E was characterised by flowers and grouped vegetables in the Cucurbitaceae family along with beans, peas, and edible flowers. Three perennial vegetable categories were created for artichoke (F), asparagus (G), and strawberry (H), which differ from each other in their soil cover, height, and presence of flowers. A category for intercropped vegetables (I) was created for fields in which multiple vegetables are grown at the same time, which is common on microfarms (Morel and Leger, 2016).

Because most farming practices of VPSs (e.g. fertilisation, tillage, sowing) already existed for cropland in the expert system, we used them for VPSs. We added or adapted weed-control practices that were specific to VPSs, such as mulching, manual/mechanical hoeing, and thermal weeding (i.e. flame, steam, or hot water), and their corresponding management options (Table 2). We also added weed-control practices specific to GHs (on the interior grassy edge). These practices are alternatives to the application of herbicides.

3.2. One-at-a-time sensitivity analysis

At habitat level I (cropland, OF, GH), mean aggregated biodiversity scores for white onion, pumpkin, artichoke, and intercropped vegetables in GH were 35%, 35%, 29%, and 27% lower, respectively, than those for winter wheat (Fig. 2). In OF, only white onion, which had the lowest soil cover, had lower biodiversity scores (−5%) than winter wheat. Pumpkin, artichoke, and intercropped vegetables had higher biodiversity scores than winter wheat, with a mean increase of 2%, 9%, and 17%,

Table 2
Habitats, farming practices, and management options in SALCA-BDA for vegetable production systems (VPSs) in the level I habitats of an open field or greenhouse in SALCA-BD. Those in bold are specific to VPSs, whereas those in italics are specific to a greenhouse.

Level II habitat	Level I farming practice	Level II farming practice	Level III farming practices	Management options
Categories A to I Green manure	Fertilisation	–	Date, quantity, type, & technique (e.g. incorporated)	For each practice
	Plant protection	Weed control	**Cover**	**No cover, organic mulch, or synthetic mulch**
			Manual/ mechanical hoeing	**Yes or no**
			Thermal weeding	
			Selective herbicide Non-selective herbicide	No herbicide, or a percentage of the area (<25%, 25% to < 50%, 50% to < 75%, or 75–100%)
		Insecticide	Date, quantity, & type	For each practice
		Fungicide	Date, quantity, & type	For each practice
		Biological pest control	Date, quantity, & type	For each practice
		Rodent control	Date, quantity, & type	For each practice
		Mollusc control	Date, quantity, & type	For each practice
	Soil tillage and sowing	–	Date, tillage type, & depth	For each practice
	Irrigation	–	–	Yes or no
	Harvest	–	Date & post-harvest material	For each practice
Interior grassy edge	*Plant protection*	*Weed control*	*Type & frequency*	*For each practice*
	Cutting	–	–	*Yes or no*

respectively. All vegetables had higher biodiversity scores in OF than in GH.

For all crops, biodiversity scores for differing management options followed a similar pattern, in which the options resulting in the highest (no weed control) and lowest scores (non-selective herbicide on 75–100% of the area) differed by 9.6% (intercropped vegetables in OF) to −11.5% (white onion in OF) (Fig. 2). All weed-control practices had lower biodiversity scores than winter wheat (no weed control), by 5.6% (organic mulch) to 11.4% (non-selective herbicide on 75–100% of the area) for white onion in OF. Synthetic mulch had more negative impact on biodiversity than organic mulch and manual/mechanical hoeing. Selective herbicides had slightly less negative impact on biodiversity than non-selective herbicides.

REF (Reference, no weed control), C1 (organic mulch), C2 (synthetic mulch), M (hoeing), SH1 (selective herbicide on < 25% of the area), SH2 (SH on 25% to < 50%), SH3 (SH on 50% to < 75%), SH4 (SH on 75–100%), NH1 (non-selective herbicide on < 25% of the area), NH2 (NH on 25 to < 50%), NH3 (NH on 50% to < 75%), NH4 (NH on 75–100%). Bold text indicates the difference between the mean score of a habitat and the mean score of cropland (the reference). The percentage variability represents the mean (±standard deviation) of the differences between each practice of each level II habitat compared to the same practice in the reference habitat.

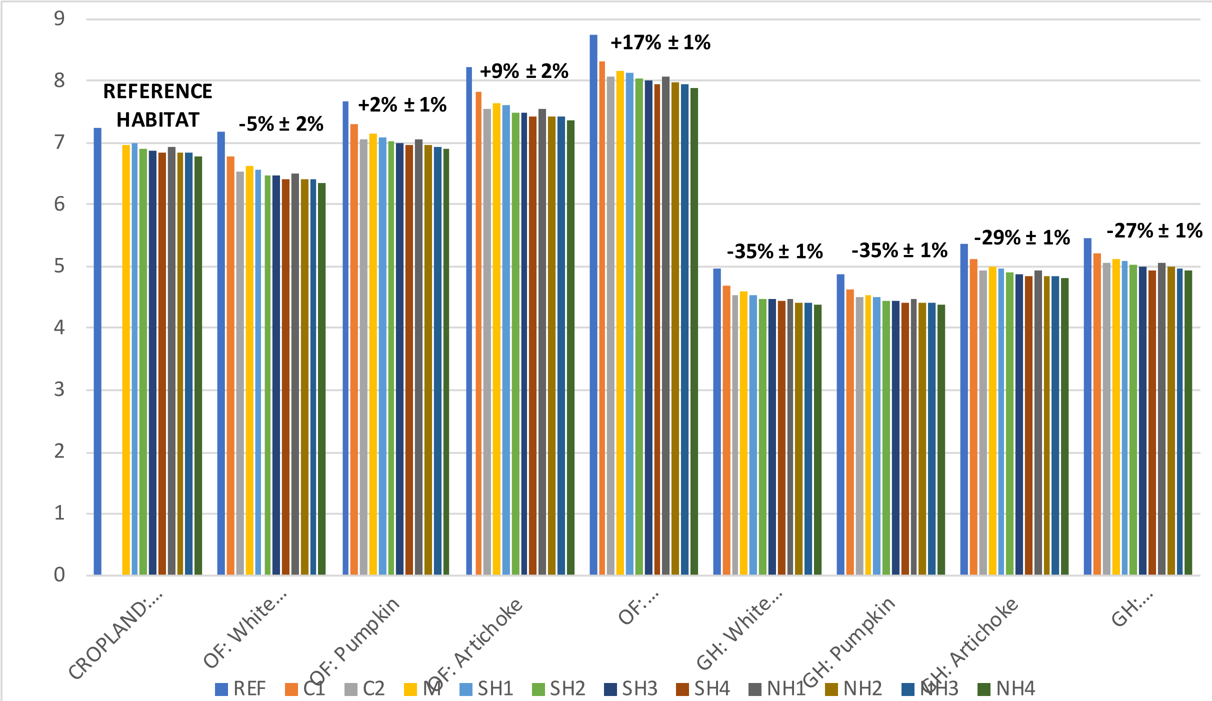

Fig. 2. Effect on the biodiversity score of the level I habitat (cropland, open field (OF), greenhouse (GH)), level II habitat (white onion, pumpkin, artichoke, intercropped vegetables) and weed-control practices.

3.3. System-level sensitivity analysis

White onion with high-intensity practices (High) had lower biodiversity scores than that with low-intensity practices (Low), in both OF and GH, for each of the ISGs and for the aggregated biodiversity score (Table 3). Two ISGs in OF (i.e. grassland flora and grasshoppers) and three ISGs in GH (i.e. grassland flora, amphibians, and grasshoppers) had a biodiversity score of 0, which corresponded to the assumptions made that VPSs are not potential habitats for these ISGs. Amphibians (in OF), mammals, snails, and wild bees were the ISGs with the lowest biodiversity scores, and with the smallest relative decrease when comparing High to Low (-40, −6%, −26%, −26%, respectively, in OF; −6%, −26%, −6%, respectively, in GH). Crop flora, birds, and spiders had the highest biodiversity scores in both OF and GH. Birds and spiders were influenced most by management intensity (-54% and −50%, respectively, in OF; −53% and −50%, respectively, in GH). Crop flora differed between the two systems by −32% in OF and −34% in GH.

Table 3
Biodiversity scores for white onion grown using low-intensity (Low) or high-intensity (High) practices in an open field or greenhouse for the 11 indicator species groups. Differences represent the percentage change in High's score compared to Low's score.

Indicator species group	Open field			Greenhouse		
	Low	High	Difference	Low	High	Difference
Field level	7.47	4.71	−37%	5.24	3.30	−37%
Crop flora	24.13	16.41	−32%	16.08	10.61	−34%
Grassland flora	0.00	0.00	–	0.00	0.00	–
Birds	9.06	4.13	−54%	3.75	1.75	−53%
Mammals	4.29	4.03	−6%	2.92	2.75	−6%
Amphibians	2.56	1.55	−40%	0.00	0.00	–
Snails	2.92	2.17	−26%	2.92	2.17	−26%
Spiders	9.85	4.92	−50%	8.10	4.03	−50%
Carabid beetles	7.95	4.66	−41%	7.25	4.39	−39%
Butterflies	5.44	3.12	−43%	3.44	2.00	−42%
Wild bees	3.00	2.21	−26%	3.00	2.21	−26%
Grasshoppers	0.00	0.00	–	0.00	0.00	–

3.4. Farm case study

The farm's score was 7.4 for its cultivated area and 14.6 when including its SNHs (Fig. 3). At the field level, potato had the lowest score (5.3) and Jerusalem artichoke (assigned to habitat category D) had the highest score (8.6). The ISGs that differed the most between these two crops were crop flora (8.4 and 22.5, respectively), spiders (9.6 and 12.5, respectively), and butterflies (0 and 4.9, respectively) (Table 4). Crop flora and spiders (many of whose species are ground-dwelling) were negatively influenced by the many tillage operations in potato. Cropland habitats, including potato, were not considered suitable for butterflies, whereas all other vegetables in OF were considered as potential habitat for them. The SNHs had scores from 20.6 (grassland) to 22.7 (hedgerow). ISGs with a high coefficient of variation (i.e. grasshopper, grassland flora, butterflies, wild bees, and amphibians) had different scores for cultivated areas and SNHs. Conversely, ISGs with a low coefficient of variation (i.e. carabid beetles, spiders, crop flora, snails, mammals, and birds) were influenced similarly (positively or negatively) by cultivated areas and SNHs.

4. Discussion

4.1. Novelties and challenges of adapting SALCA-BD to VPSs

The expert system is based on the concept of a field occupied by a crop or crop rotation. Individual VPSs can grow many vegetables (e.g. ca. 40 on diversified farms) (Pépin et al., 2021). The literature review did not yield information that would have allowed us to define habitat coefficients for all vegetables, and the experts confirmed this point. Because an expert system with too many categories is not user-friendly, clustering vegetables according to their characteristics provided an operational solution for SALCA-BD. Although these clusters already contain 40 vegetables, they can be adapted by adding other vegetables, as we did for Jerusalem artichoke in the case study. Some farms, especially microfarms, have small fields with intercropped vegetables (Morel and Leger, 2016). Because each vegetable covers too little area to

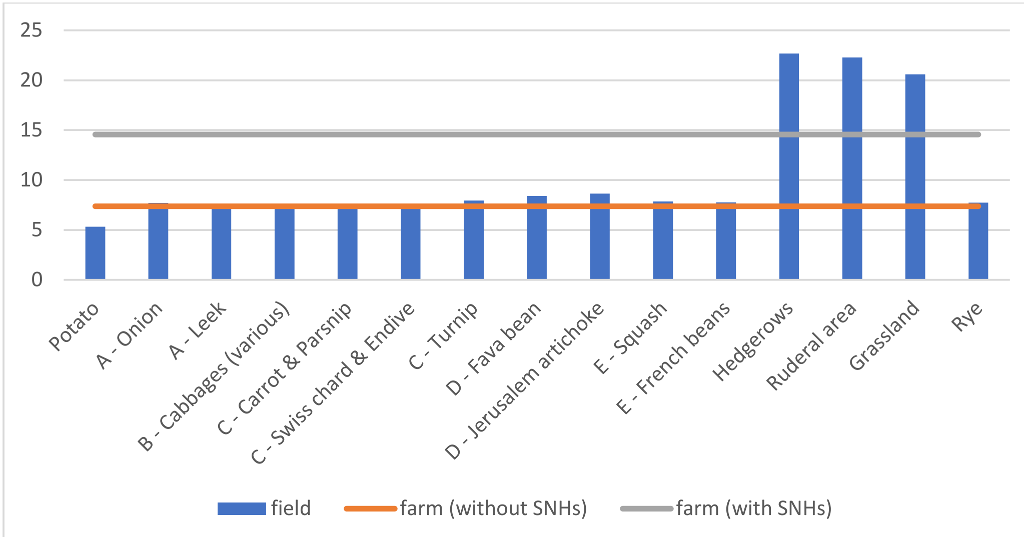

Fig. 3. Biodiversity scores for individual crops and semi natural habitats (SNHs) of an organic vegetable farm, and whole-farm results with and without the inclusion of SNHs. The capital letter before the name of each vegetable refers to its category.

perform a meaningful assessment, we created the intercropped vegetable category to represent such a field as a single habitat, whose value to biodiversity is expressed in its habitat coefficients (Pereira et al., 2015; Sokos et al., 2013). To estimate the habitat coefficients of this category, we considered a field with vegetables of different heights, soil cover, durations, and blooming periods, as usually found on small organic farms. The literature and experts did not suggest creating several categories to represent different intercrop compositions. Ultimately, nine vegetable categories were created.

Most of the practices in VPSs were similar to practices in cropland. Only weed control differed greatly, as vegetable farmers commonly cover the soil with organic or synthetic mulch. In terms of impacts on biodiversity, the main advantage of mulching compared to hoeing and thermal weeding is that it disturbs the soil less (Alyokhin et al., 2020). Mechanical hoeing requires machines that may compact the soil and disturb ground-dwelling fauna (Rivers et al., 2016). Thermal weeding is often used along with mechanical weeding to increase the effectiveness of weed control (Fontanelli et al., 2013); however, as the experts confirmed, it can negatively impact local faunal biodiversity.

The literature review did not provide enough detailed information to parametrise every aspect of the inventory and control table. Most studies of impacts of a farming practice on the abundance of an organism focused on pest management, not biodiversity. Fortunately, the interviews with the experts filled knowledge gaps. During these interviews, the challenge consisted of distinguishing direct impacts from indirect impacts, which was sometimes difficult. For example, the experts considered that hoeing can have a negative impact on birds (rating of 2), not only because it disturbs the birds themselves (a direct impact), but also because it can have negative impacts on the insect prey of birds (an indirect impact).

4.2. Impacts of weed-control practices: sensitivity analysis

The OAT sensitivity analysis indicated that all vegetables are worse for biodiversity when they are in GH instead of OF. For the modified control table, we assumed that increasing openness of a habitat favours the exchange of species with surrounding habitats. The habitat coefficients of OF and GH influence the biodiversity score, and these results are consistent with the expert system's assumption that habitat influences biodiversity more than weed-control practices. Martin et al. (2020), who studied effects of six farming practices, field size, and crop diversity on eight taxonomic groups in farmland in Ontario, Canada, also observed that habitat type, defined by field size and crop diversity, can influence biodiversity as much or more than management practices.

The fact that scores of all level II habitats followed the same pattern as the weed-control practices changed (Fig. 2) indicates that parametrisation of the expert system for VPSs is consistent with that for cropland. The biodiversity scores of vegetables varied less in GH than in OF because a GH has an inherently lower biodiversity potential than an OF. Indeed, an OF provides more opportunities for species to colonise it from the surroundings than a (partly) closed GH does, as expressed by the habitat coefficient. Intercropped vegetables had the highest biodiversity scores in both OF and GH, which aligned with the habitat coefficients assigned. Intercropped vegetables provide high variability in resources in space and time, which favours, for example, populations of solitary bees (Baños-Picón et al., 2013).

For a given habitat category, biodiversity scores varied little as a function of weed-control practices. Indeed, changing a single practice cannot have a large effect in SALCA-BD due to the small range of its scoring scale (i.e. 1–5). A more specific example is the small difference between the application of selective and non-selective chemical herbicides, for which the scoring scale was even smaller (i.e. 1–3), since no information was found to support a positive effect of any type of herbicide on biodiversity, which excluded ratings of 4 and 5. Synthetic mulch had a more negative impact on biodiversity than organic mulch, based on results of Summers et al. (2010) and Madzaric et al. (2018). They observed that organic mulch in a vegetable field was associated with more spiders than plastic mulch or bare soil was, and that high humidity and moderate temperatures, as found on soil covered with organic mulch, would foster the growth of spider populations.

4.3. Impacts of management intensity: system-level sensitivity analysis

The high-intensity field of white onion influenced biodiversity more than the low-intensity field, which was also observed in cropland by Geiger et al. (2010), who found that agricultural intensification had major negative impacts on the species richness of wild plants, carabids, and birds. In the present study, SALCA-BD estimated large decreases in the biodiversity score for crop flora, carabids, and birds in high-intensity fields (32%, 41%, and 54%, respectively). The higher biodiversity score of white onion for crop flora than for the other ISGs resulted from its low soil cover, which favours crop flora. When Jeanneret et al. (2014) applied SALCA-BD to winter wheat of different management intensities, the increase in intensity decreased bird and spider species richness, as in

Table 4
Biodiversity scores at field and indicator species group (ISG) levels of the organic vegetable farm case study. The capital letter before the name of each vegetable refers to its habitat category.

Indicator species group	ISG score	Potato	A - Onion	A - Leek	B - Cabbages (various)	C - Carrot & Parsnip	C - Swiss chard & Endive	C - Turnip	D - Fava bean	D - Jerusalem artichoke	E - Squash	E - French beans	Hedgerows	Ruderal area	Grassland	Rye	Coefficient of variation
Field level		**5.3**	**7.7**	**7.6**	**7.6**	**7.2**	**7.5**	**7.9**	**8.4**	**8.6**	**7.9**	**7.8**	**22.7**	**22.3**	**20.6**	**7.7**	
Crop flora	17.0	8.4	23.2	22.7	18.5	17.1	18.1	19.8	22.1	22.5	18.5	18.1	0.0	27.0	0.0	18.7	47%
Grassland flora	24.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.8	27.0	21.4	0.0	208%
Birds	15.7	11.1	9.8	9.7	11.9	11.0	11.5	12.1	13.8	13.6	12.5	12.5	43.3	30.0	30.4	12.8	60%
Mammals	8.3	6.8	6.6	6.6	6.6	6.5	6.6	6.6	6.6	6.6	6.6	6.6	19.0	22.4	13.0	7.0	57%
Amphibians	3.4	2.1	2.2	2.2	2.2	2.2	2.2	2.3	2.4	2.2	2.2	2.2	10.4	16.6	9.3	2.2	104%
Snails	4.4	2.7	2.7	2.7	4.8	4.7	4.7	4.9	2.5	2.9	4.7	4.7	7.1	10.4	11.0	2.6	55%
Spiders	13.6	9.6	10.3	10.0	11.6	11.1	11.5	11.8	11.4	12.5	11.5	11.3	32.7	17.6	26.4	10.5	48%
Carabid beetles	15.7	11.3	11.3	11.2	13.4	12.5	13.0	13.3	10.8	12.7	11.5	11.5	33.4	21.4	29.4	16.1	45%
Butterflies	11.4	0.0	3.7	3.7	3.6	3.7	3.7	4.3	6.0	4.9	4.9	4.9	41.0	16.0	37.3	0.0	139%
Wild bees	5.7	4.1	2.7	2.7	2.7	2.6	2.7	2.8	5.8	5.4	5.4	5.4	13.6	32.4	24.1	5.6	113%
Grasshoppers	29.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	31.7	15.2	29.5	0.0	217%

the present study. Because many spiders can live on plants or the ground (Simonneau et al., 2016), they are influenced by a wider range of management practices. Unsurprisingly, changing the entire production system influenced the aggregated biodiversity score at the field level more than changing only weed-control practices. This aligns with the holistic approach that Altieri and Rosset (1996) describe as necessary in the perspective of an agroecological transition.

4.4. Importance of SNHs in the landscape

Changing farming practices may improve the biodiversity score to a certain extent. At the farm level, however, SNHs had higher scores than cultivated fields, regardless of the farming practices; thus, SNHs improved the farm scores greatly. Their importance of SNHs in the landscape for biodiversity has been reported for a variety of ISGs (Baños-Picón et al., 2013; Billeter et al., 2008; Burel et al., 2004; Chaplin-Kramer et al., 2011; Chiron et al., 2010; Hendrickx et al., 2007; Jeanneret et al., 2021; Rischen et al., 2021; Tscharntke et al., 2005). Nemecek et al. (2011) used SALCA-BD to compare organic and conventional fields and concluded that lower-impact practices cannot entirely compensate for a lack of SNHs. Combining low-intensity farming with the presence of SNHs enhances the biodiversity of farming landscapes.

4.5. Limits of the expert system and prospects for development

SALCA-BD performs analyses at field and farm levels to calculate individual and aggregated ISG biodiversity scores. It considers detailed farming practices applied to crops and SNHs. Estimating impacts at a fine level can distinguish between fields or farms that have the same land use and similar management intensities.

Most existing methods focus on a single taxon, mainly vascular plants (e.g. Knudsen et al., 2017; Mueller et al., 2014), whereas SALCA-BD assesses 11 ISGs. In comparison, Chaudhary et al. (2015) and Chaudhary and Brooks (2018) estimated CFs for five ISGs. The ISGs reacted differently to practices and habitats, making assessment of multiple ISGs useful for assessing biodiversity as widely as possible (Lüscher et al., 2017). However, SALCA-BD does not consider soil biodiversity (e.g. microorganisms, nematodes, earthworms), which is also influenced by farming practices (Tsiafouli et al., 2015) and plays a key role in shaping aboveground biodiversity (Bardgett and van der Putten, 2014) and sustaining agro-ecosystem functioning (Brussaard et al., 2007). Including impacts of farming practices and habitats on soil biodiversity in SALCA-BD would widen the scope of its assessments and increase their value.

SALCA-BD also does not consider spatial issues such as the size or spatial arrangement of fields. Lüscher et al. (2017), who compared SALCA-BD biodiversity scores to on-farm species observations, found that data for mobile ISGs (i.e. spiders and wild bees) correlated at the field level but not the farm level, which suggests an influence of spatial issues that SALCA-BD does not consider. Farmland biodiversity is enhanced by small fields (Fahrig et al., 2015; Martin et al., 2020; Šálek et al., 2018) and fields with a higher perimeter:area ratio (Clough et al., 2020). SALCA-BD considers field size indirectly when assessing an entire farm, as farms with smaller fields tend to have a higher ratio of SNH area to cultivated area than farms with larger fields. This higher perimeter: area ratio gives more weight in the aggregation to SNHs on farms with smaller fields, which yields a higher biodiversity score. Field size is considered indirectly only when SNHs are included. These spatial aspects could be included in SALCA-BD by attributing additional points for small fields, following the example of bonus points attributed for soil cover.

Finally, the expert system assesses only impacts on biodiversity at the farm level that result from direct effects of farming practices, thus ignoring indirect impacts upstream and those downstream of the farm gate (Bockstaller et al., 2015). Conversely, methods based on global CFs (Chaudhary and Brooks, 2018) can estimate potential species loss on land used for upstream processes (e.g. production of seeds or animal feed), but they cannot estimate in detail impacts of specific changes in production practices applied to individual crops. Thus, combining SALCA-BD with a comprehensive method would be useful. Bystricky et al. (2020) combined SALCA-BD (Jeanneret et al., 2014) and the method of Chaudhary and Brooks (2018) to create a complementary analysis, as the two methods addressed different aspects of their research question. SALCA-BD allowed them to compare scenarios in detail, while the other method included upstream impacts in its predictions. The authors concluded that more research is needed to combine the two methods.

5. Conclusion

This study showed that SALCA-BD can model VPSs when vegetables with similar characteristics are grouped into a single habitat. Few studies in the literature have investigated impacts of VPSs and their associated practices on biodiversity. The farm case study highlighted the importance of SNHs and low-intensity practices for enhancing biodiversity. SALCA-BD considers field size indirectly when assessing an entire farm, including its SNHs. Consideration of spatial issues and soil biodiversity would increase the value of SALCA-BD. Due to its detailed consideration of habitats and practices, SALCA-BD is useful for assessing biodiversity at field and farm levels and for ecodesign. Impacts of the background system could be considered by combining SALCA-BD with comprehensive methods for assessing biodiversity.

CRediT authorship contribution statement

Antonin Pépin: Conceptualization, Methodology, Software, Writing – original draft. **Maria Vittoria Guidoboni:** Conceptualization, Methodology, Writing – original draft, Visualization. **Philippe Jeanneret:** Conceptualization, Methodology, Writing – review & editing. **Hayo M. G. van der Werf:** Conceptualization, Methodology, Writing – review & editing.

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

The data that has been used is confidential.

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Appendix A. Supplementary data

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