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Selected farm-level crop protection practices in Europe and Argentina: Opportunities for moving toward sustainable use of pesticides

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ABSTRACT

Extensive use of plant protection products (PPP) in the last decades contributes to negative impacts on ecosystems, animals and humans. For the strategies of PPP reduction and replacement of hazardous pesticides, farm-level data on agronomic management practices and crop protection applications are crucial. In this study, we strategically collected data for the 2021 season at the SPRINT project case study sites (CSS) in 10 European countries and Argentina, on perennial, arable and vegetable crops. Data collection included strategically selected farm and field data, pesticide records and farming practices. Results involved more than 1700 recorded PPP applications across various crops with more than 170 different active substances from PPP in organic, integrated pest management and conventional farming practices. We explored differences in application patterns (fungicides, insecticides, herbicides and non-PPP, e.g. adjuvants, growth regulators, and fertilizers) between and within crops, countries and farming systems and calculated the costs of PPP use. The pesticide dosages applied during the crop season varied up to a factor of 20 around recommended doses. Regarding the costs of PPPs use perennial crops had the highest costs per ha crop production area. Finally, we analysed the active substances applied in different farming systems in terms of their hazard statements. Our results shed light on how PPPs are used across different crop and farming types and will help elucidate how pesticide application patterns can be changed in the future. Finally, we highlighted non-PPP use practices which help to reduce dependency on PPP use. This might be used to support decision-making and policies within agricultural advisory/support systems.

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1. Introduction

In the last decades, massive use of plant protection products (PPPs) led to current issues regarding negative impacts on human health, soil and water ecosystems (Fantke and Jolliet, 2016; Kosnik et al., 2022). In Europe, 355′175 tonnes of PPP were used in 2021 (Eurostat, 2021) despite substantial efforts at national and European level to reduce PPP usage. In Argentina, 241′519 tonnes of pesticides were applied in 2021 (Food and Agriculture Organization of the United Nations, 2021). The reduction of the use of PPP in Argentina is suggested by the scientific field, but there is no clear decision by the National State in this regard so far. The impacts of PPP use on the environment and human health call for urgent reduction of pesticide use in arable and horticultural cropping systems (Tang et al., 2021. In addition, the evolution of disease and pest resistance to pesticides due to repetitive use of chemicals becomes more and more critical for food security and safety. In particularly, it poses a great threat if pests and diseases cannot be controlled sufficiently, and if pest/disease calamities become more frequent due to climate change and invasive noxious organisms. As a consequence, new strategies to foster more sustainable use of pesticides, such as the EU Green Deal (Tataridas et al., 2022), were adopted. Several studies have shown how the transformation of agriculture can lead to a more sustainable use of pesticides (Hofmann et al., 2023; Lee et al., 2019).

A range of plant protection tools and strategies to reduce pesticide use are available (Pertot et al., 2017). Those methods include plant/crop resistant varieties, crop rotation, mechanical weed control, biocontrol agents (macrobials, microbials and natural substances), semiochemicals, physical mating disruption, decision support systems (Delière et al., 2015), chemical substitution (Steingrímsdóttir et al., 2018a) and monitoring (Lamichhane et al., 2016)). For example, diverse crop rotations are an essential tool to increase the resilience of crops and preventively reduce risks due to pests and diseases. Today, the adoption of available tools and techniques is still limited especially in mainstream agriculture. Hurdles for adoption include availability of tools for key pests, high costs, limitations in efficacy and trust by farmers (Meissle et al., 2010; Moss, 2019).

Despite the importance of pest control for yield security and food safety, there is very little detailed information publicly available about PPP use and application in the various crops under highly diverse pedo-climatic conditions across Europe. The lack of PPP application data was highlighted as part of the proposal for a sustainable pesticide use regulation (European Union Law, 2022) requiring that detailed standardized PPP use information becomes available in the future. Furthermore, detailed and representative data on PPP use are a pre-requisite to characterize current best farming practices and to relate PPP use to potential impacts on the environment and human health. Such data will help understand how, why and in which frequency and amounts pesticides are used to develop plausible strategies which aim to reduce pesticide use. Moreover, such data is useful to reexamine the European models relative to workers exposure, which currently use default values. Plant protection strategies are always crop-specific, adapted to the pedo-climatic conditions and embedded in a specific economic and legal context. To understand current farming practices, to identify currently available best practices, and to explore the potential impacts of future tools and techniques, it is crucial to understand these agronomic and economic contexts. Although access to pesticide-use data will be improved by the European Commission (Mesnage et al., 2021), there is still a lack of information regarding the agronomic management practices over a whole season on different crops and different countries, with sufficient details to support risk assessment and management from farm to national level.

The main goal of the present study is to identify options to move towards a more sustainable use of pesticides in selected scenarios. To achieve this goal, we identified four specific objectives: (i) to collect and synthesize real-life farm-level pesticide use data and management strategies across 11 countries; (ii) to assess differences in type and application time of pesticides in different crops and cropping systems and related costs; (iii) to provide the link between PPP application and sustainable PPP management identification, and (iv) to assess differences in hazard statements of PPP applied in conventional, integrated pest management and organic farming systems.

2. Materials and methods

Case study sites (CSS) covering relevant European climatic zones (North, Central, South) comprising a set of local farms were strategically selected for this study in 10 European countries and Argentina (CSS-1 Spain, CSS-2 Portugal, CSS-3 France, CSS-4 Switzerland, CSS-5 Italy, CSS-6 Croatia, CSS-7 Slovenia, CSS-8 Czech Republic, CSS-9 Netherlands, CSS-10 Denmark, CSS-11 Argentina). The selection of the farms was based on the needs coming from the design of the SPRINT sampling campaign (Silva et al., 2021) and Argentina as first rough cross-evaluation of practices against a single country outside Europe. Between 10 and 19 commercial farms were selected per country, with one or two representative fields selected for each farm. Farms were categorized according to the farming practices and included conventional, integrated pest management (IPM) and certified organic farms. Farms were strategically selected based on the willingness of farmers to participate and to represent current farming practices in different farming systems as well as the key crops in the respective climatic zones: vegetables (Spain, Italy), grapevine (Portugal, France), fruits (Switzerland), olives (Croatia), arable crops with focus on cereals and oil seed plants (Slovenia, Czech Republic, Denmark, Argentina) and potatoes (Netherlands). Data collection for the cropping season 2021 was conducted by CSS teams between April 2021 and January 2022. Face-to-face interviews with farmers were performed at farm level using a standardized questionnaire protocol (Silva et al., 2021), Fig. 1 step 1 and 2.

The questionnaires included six topics of farm and crop activities. Each section was designed to get clear evidence on pest control strategy performed by farmers and understand whether a strategy was more likely used. The six topics were as followed.

(i) General information such as the type of farming practice, size of farm and of fields, types of crops and livestock, as well as working capacity (employees).
(ii) For a selected one or two fields (where also the samples were taken), a detailed description of the agronomic activities and yield parameters was compiled, which included crop and variety and e.g. position in crop rotation, as well as all crop-specific activities such as tillage, fertilisation, irrigation, pruning, and sowing.
(iii) Activities related to crop protection were requested in detail, including but not limited to the use of PPP formulations and related tools and techniques, and the strategy and motivation of the farm manager for PPP applications. The assessment of the crop protection strategy on the respective fields included variety, dates of PPP applications, product tank mixtures, type of products, product brand name, product distributor, target organisms, mode of action, area treated, quantity of product applied, total volume applied (total tank volume: product and water volume), formulation, active substances and concentrations, technique of application, speed of application, type of nozzles, and costs of products applied.
(iv) Soil fertility management assessment included pre-crop, dates of application, types of product and nutrient specifications (NPK, micronutrients) as well as quantities applied. The information on agronomic practices was compiled in a ‘log book’, which listed all agronomic management practices on the respective fields during the whole season from planting/sowing to harvest as well as the underlying assumptions and motivations.

(vi) Finally, econometric data included costs (products, infrastructure, machineries, and working capacity), gross and marketable yield, farm gate prices as well as profit margins.

Raw data was thoroughly screened for completeness, plausibility and data integrity (Fig. 1 step 3), and revised/supplemented where necessary by the CSS teams with the help of the respective farms (appendix 1). Missing/unknown data was tagged and complemented where possible with proxies from e.g. product technical leaflets to allow for subsequent analysis (appendix 1 for more details). The data set was further complemented with related publicly available data, such as phenological codes (BSV, 2021; Schweizerische Eidgenossenschaft, 2021), standard codes for crops and pests (EPPO secretariat, 2022.), mode of action of active substances and resistance risks (FRAC Committee, ; HRAC Committee, ; IRAC Committee, ; Sparks and Nauen, 2015), and application recommendations of PPPs and fertilizers (collection of regional crop-specific or manufacturer-specific technical leaflets), (Fig. 1 step 4). If expenditures for PPPs were not available, costs for PPPs were assessed based on publicly available catalogues issued by manufacturers or regional PPP distributors. Moreover, data was complemented by hazard statements of active substances by following the work done by (Burtscher-Schaden et al., 2022).

A coherent MS-Access database was compiled (https://doi.org/10.5281/zenodo.12526872) to ensure data integrity and open source access in the future (Fig. 1 step 5). To comply with data protection requirements and to ensure anonymity, information related to individual farms was coded prior to further data processing or analysis. To facilitate future analysis and data mining, a set of standardized data queries was specified. In this study, a straightforward descriptive statistical analysis (Fig. 1 step 6) was performed to characterize the eleven CSS with respect to crops, pests, and pesticide use data.

3. Results

3.1. Description of case study site data

In total, 135 farms were involved in the study and data for 178 fields was collected in the eleven CSS comprising detailed information on farm crops (e.g. size of field, farm type, crop rotation), field activities (e.g. soil cultivation, mechanical weeding), fertilizer, non-plant protection products (e.g. growth regulator, chelators), and pesticide use data (Table 1). Details on the recovery of data collection, missing data, and quality of responses are described in appendix 1. A total of 28 different crops and their related production practices were assessed, covering the 2021 cropping season. Crops analysed in this study are listed in Table 2. Six perennial crops were included: grapevine in France and Portugal, olives in Croatia and apple, pear, cherry and plum in Switzerland. A total of 22 annual crops was assessed, including a range of vegetables in Spain and Italy, potatoes in the Netherlands and arable crops (cereals, oilseed crops) in Czech Republic, Denmark, Slovenia and Argentina. The number of farms with the same crop ranged from 1 (chickpea) to 22 (grapevine). Farming practices included conventional, organic and IPM (Integrated Pest Management) production, but also farms in transition to organic or farms running two production practices in parallel.

A wide range of farm sizes are represented in the CSSs ranging from small farms (e.g. 1 ha in Portugal for grape production) up to very large farms (e.g. 2000 ha in Argentina for cereal production). The farm size varied depending on crop and country, i.e. farms in Portugal, Italy, Croatia up to 20 ha, Spain, France, Switzerland, Slovenia, Netherlands ranging between 20 ha and 100 ha, whereas the mean farm size in Czech Republic, Denmark, and Argentina was larger than 100 ha. Most farms in the CSSs were operated by full-time employees, and the available work force is directly linked to the farm size and the business branches.

The yields reported by the CSSs indicate that the selected farms and fields are managed in a representative way since the reported yields largely correspond to reference values (Food and Agriculture Organization, 2021.). However, the reported yields vary largely between farms. For example, yields in apple varied between 25 and 40 t/ha, in broccoli between 10 and 33 t/ha, cabbage 5.71 and 50 t/ha, and olives 0.2 t/ha and 6.31 t/ha. More details on farm specific data can be found in the database (https://doi.org/10.5281/zenodo.12526872).

3.2. On-farm uses of PPPs

A total of 176 different PPP active substances (a.s.) and biocontrol organisms (Stenberg et al., 2021)/macrobials (Sundh and Goettel, 2013) were applied during the 2021 season, of which 51 active substance are currently authorized in organic agriculture, whereas 126 active substance can be legally used in conventional/IPM production only. A total of 49 fields assessed out of 178 did not report any PPP use during the considered cropping season. The reason is that no treatments in such fields were performed by farmers (mentioned as "no treatments" in

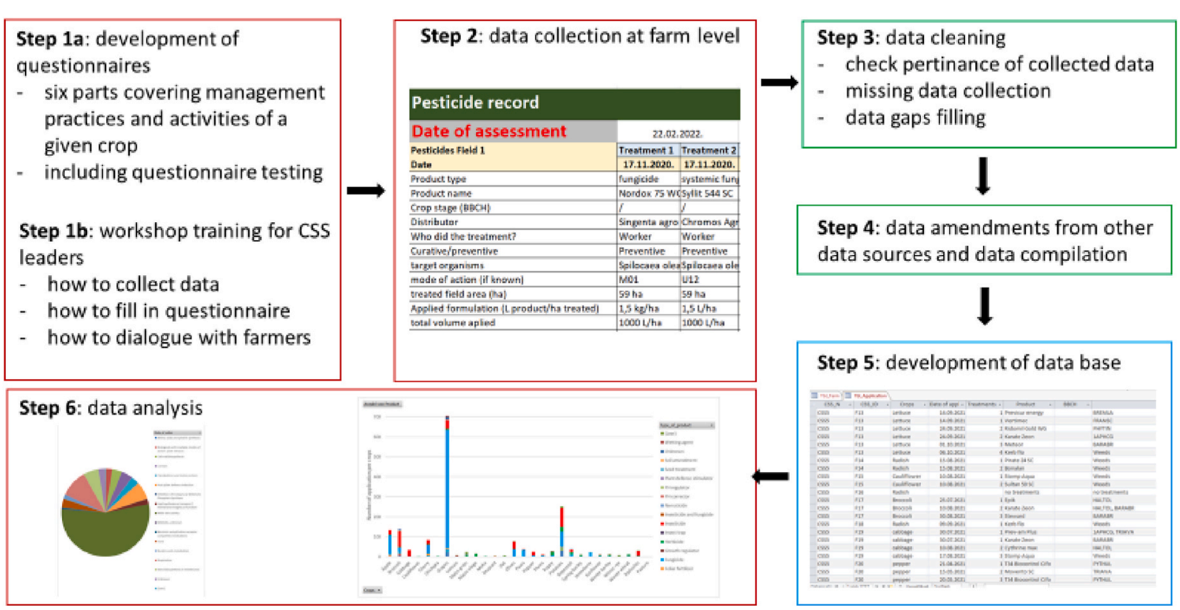

Fig. 1. Workflow from data collection, data curation, data gap filling, dataset enrichment, and analysis.

Table 1
Summary statistics of collected data across farms.

	CSS1	CSS2	CSS3	CSS4	CSS5	CSS6	CSS7	CSS8	CSS9	CSS10	CSS11
Climatic zones	Northern, Central, Southern zones, West to East Europe and Argentina										
Number of farms	12	10	10	8	11	18	12	13	15	12	14
Number of fields[a]	15	10	12	12	18	19	24	18	15	20	15
Average size of farms (ha)	97	10	39	23	19	6	54	313	85	255	547
Number of crops	1	1	1	5	6	1	3	4	1	5	7
	28 different crops (4 main crop types, perennials, vegetables, cereals, oilseed crops)										
Farming systems[b]	Conventional: 33 % (2.2% in transition to organic) Organic: 44.1% IPM: 12.8% Others: 7.3%										
Number of reported PPP interventions[c]	1718 interventions in total across all CSS fields for the 2021 cropping season										
Number of PPP active substances	176 (contained in 400 PPP formulations) Insecticides: n = 114 Fungicides: n = 195 Herbicides n = 67 Other a.s.: n = 21 Other than PPP[d]: n = 38										
Pests and diseases	80 pests[e] and diseases managed by PPP use										

Cereals: 0–8 pests/diseases/weeds.
Perennials: 4–19 pests/diseases/weeds.
Vegetables: 1–11 pests/diseases/weeds.
Oilseed crops: 7–14 pests/diseases/weeds.
Detailed data for each farm can be found on zenodo (https://doi.org/10.5281/zenodo.12526872).
[a] Average number of fields per country: n = 16; Min = 10; Max = 24.
[b] Farming systems are described in appendix 2.
[c] PPP intervention is the application of a given pesticide at given day.
[d] Other product used in the protection strategy which are not PPPs include adjuvants, insect traps, Other substances than PPPs include fertilizers, pH regulators, chelators, wetting agents.
[e] Ranges per main crop types (and per pest type, pathogens-insects).

questionnaires) in CSS9 for potatoes (only organic farms), CSS7 for maize grain and maize silage (only organic farms), CSS6 for olives (only organic farms), CSS10 for cereals (3 conventional and 6 organic farms), CSS11 for cereals (2 organic and 3 conventional farms). Another reason of non-report of PPP use was that farmers did not communicate their PPP interventions as in CSS5 in vegetables (1 organic and 3 IPM farms) and in CSS8 in oilseed crops (4 organic farms).

The intensity and diversity of active substance use largely depends on the crop and its plant health state. In vegetable crops (broccoli, cabbage, cauliflower, lettuce, pepper, potatoes and radicchio), between 2 and 31 different active substance were used, indicating the high diversity of crop pests and diseases in vegetable crops. In arable crops including chickpea, maize grain, maize silage, moha, mustard, oat, poppy, rapeseed, barley, sunflower, rye and wheat, 2 to 25 different active substance were used per crop. In perennial crops (apple, cherry, grapes, olives, pears, plums and strawberry), 5 to 72 active substance per crop were reported. The data indicate that the highest number of different active substance was applied in grapes (72 different active substance, with 4–21 different active substance per farm) and in potatoes (31 different active substance, zero to 17 different active substance per farm). Within a specific crop, the number of different active substance used varied largely across farms (Table 2).

The intensity of PPP as defined by the frequency of interventions (number of times farmers sprayed a pesticide or mixture of pesticides) with active substance varied largely between crops and production types. In this study, a total of 1718 PPP interventions was assessed (Fig. 2).

On average, 41 applications per field were reported over the 2021 cropping season for apple production (Table 2), followed by pears with 38 applications, and grapes with 34.3 applications. In annual crops, potato (15.1 applications) was followed by rapeseed (12) and sunflower (2.8), whereas for rye only 0.5 average applications per farm were reported. Farmers used not only PPP, but also other supportive substances including leaf fertilizers, chelators, growth regulators or biostimulants. We found 27 additional applications other than PPPs in grapes, 21 in cherries1 and 17 applications in broccoli.

Regarding cumulative frequency of use of products (including PPPs and non-PPPs (e.g. fertilizers, adjuvants, growth regulators) (Fig. 2), we found an annual average of 50 applications in apple crops, followed by pears, grapes and cherry. Potato requires intensive use of fungicide and insecticides, whereas use of PPPs in cereals, oilseed crops and some vegetables was limited to 5 applications. Fungicide use was predominant in perennial crops (apple, pears, grapes, cherry, strawberries, plums and olives), whereas insecticide use was more important in vegetable crops (pepper, potatoes, cabbage, radicchio). Herbicides were representing a major pesticide group in arable crops. Non-PPPs such as bio stimulants or foliar fertilizers were predominantly applied in high value crops such as apple, grapes, cherry, potatoes and broccoli.

In practice, individual PPP active substance are often combined in branded product formulations or combined by farmers in tank mixtures. For example, a tank mixture may contain 2 or 3 fungicides and 1 or more insecticides. The number of interventions with tank mixtures provides an indicator for the intensity of crop protection interventions; the number of interventions depends on the diversity of the pest/pathogen pressure level and the duration of the cropping season. We found most interventions in apple and pears with an average of 24 and 25 interventions during the cropping season. In arable crops, the number of interventions varied between 0.1 (oat) and 5.5 (potatoes), in oilseed crops between 1.3 (sunflower) and 6.3 (oilseed), and in vegetables between 2 (lettuce) and 9.5 (pepper).

The quantity of PPP use per field and season depends on application frequency as well as on the authorized application rate. In pears and apple, 150.7 kg per ha and 121.9 kg active substance per ha during the growing season was reported, respectively. In contrast, less than 2 kg active substance per ha was applied in most arable (excepted potatoes) and vegetable crops.

3.3. PPP active substances usage and product properties

In total, 176 different active substance (fungicides, insecticides,

Table 2
On-farm uses of Plant Protection Product (PPP) arable, vegetables, fruit and grapevine production in conventional, IPM and organic systems
Number of applications and active substances (a.s.) were reported per crop. Average PPP, active substance, interventions and yield were calculated for each crop.

Crops	Number of field	Number of different a.s. applied	a.s. unknown, no info	average sum of number of applications of a.s.	% of fields with no applications	Number of non-PPP applications (other than PPP, fertilizer, growth regulator, chelator)	Range Number of a.s per field		Range of applications per fields		Treatment interventions[a]			a.s use kg/ha				Number of pests	Yield					
							Min	Max	Min	Max	average	Min	Max	Average a.s kg/ha per field	Average a.s kg/intervention	Min	Max		yield average t/ha	Min	Max	yield average L/ha	Min	Max
Apple	3	22	0	41.0	0.0	21	4	16	37	48	24.00	22	25	121.86	5.08	59.06	188.09	12	32.50	25	40			
Broccoli	16	29	0	8.2	0.0	17	1	10	2	14	3.38	2	7	1.13	0.34	0.00	3.60	8	15.62	10	33			
Cabbage	4	10	0	8.5	0.0	0	2	4	4	22	5.00	3	11	0.53	0.11	0.25	1.22	7	29.89	5.71	50			
Cauliflower	1	2	0	2.0	0.0	0	2	2	2	2	2.00	2	2	1.91	0.96	1.91	1.91	1	20.00	20	20			
Cherry	5	20	0	13.6	0.0	21	4	11	5	20	8.80	7	14	43.33	4.92	8.51	71.78	12	9.40	9	10			
Chickpea	1	2	0	4.0	0.0	0	2	2	4	4	4.00	4	4	4.52	1.13	4.52	4.52	1	1.20	1.2	1.2			
Grapes	22	72	5	34.3	0.0	27	4	21	4	68	11.77	6	20	33.92	2.88	1.12	66.87	19	4.56	1.2	12	3272.73	1000	6100
Lettuce	2	10	0	5.0	50.0	0	0	10	0	10	2.00	0	4	1.60	0.80	0.00	3.21	8	10.00	10	10			
Maize grain	12	9	0	0.8	75.0	0	0	7	0	7	0.83	0	5	0.54	0.65	0.00	2.76	2	7.00	3.5	10			
Maize silage	14	7	0	2.1	14.3	0	0	3	0	3	1.00	0	2	0.58	0.58	0.00	1.88	1	35.71	30	40			
Moha	1	2	0	4.0	0.0	0	2	2	4	4	2.00	2	2	5.28	2.64	5.28	5.28	1						
Mustard	4	2	0	0.5	75.0	0	0	2	0	2	0.50	0	2	0.07	0.14	0.00	0.28	2	1.15	0.7	1.98			
Oat	7	2	0	0.3	85.7	0	0	2	0	2	0.14	0	1	0.01	0.06	0.00	0.06	1	3.52	1.7	5			
Olives	19	17	0	4.1	10.5	0	0	9	0	13	3.58	0	12	7.34	2.05	0.00	100.00	7	1.49	0.2	6.31	179.47	15	400
Pasture	1	0	0	0.0	100.0	0	0	0	0	0	0.00	0	0	0.00	0.00	0.00	0.00	0						
Pears	1	5	0	38.0	0.0	0	5	5	38	38	25.00	25	25	150.65	6.03	150.65	150.65	4						
Pepper	2	13	0	12.5	0.0	0	1	12	2	23	9.50	2	17	0.85	0.09	0.10	1.61	9	7.99	7.81	9.75			
Plums	1	10	0	11.0	0.0	0	10	10	11	11	5.00	5	5	47.01	9.40	47.01	47.01	9	20.00	20	20			
Poppy	6	12	0	5.5	0.0	2	2	8	2	12	3.17	1	6	0.88	0.28	0.54	2.23	8	3.37	0.68	8.1			
Potatoes	15	31	0	15.8	46.7	18	0	17	0	46	5.47	0	17	9.89	1.81	0.00	27.34	11	33.54	25	45			
Radicchio	8	8	0	3.6	37.5	0	0	3	0	22	2.25	0	11	0.91	0.41	0.00	2.88	5	9.17	0.75	18			
Rapeseed	4	25	0	12.0	0.0	1	9	11	10	15	6.25	5	10	1.43	0.23	0.70	2.10	14	3.19	2	3.82			
Spring barley	4	8	0	3.0	50.0	0	0	7	0	7	1.00	0	2	0.39	0.39	0.00	1.37	2	6.00	3	7.5			
Strawberry	2	12	0	11.5	0.0	0	6	6	10	13	6.00	5	7	7.58	1.26	2.97	12.19	5	6.00	2	10			
Sunflower	4	9	1	2.8	25.0	0	0	4	0	4	1.25	0	3	0.42	0.34	0.00	1.35	7	2.39	0.14	3.5			
Winter barley	7	11	0	1.4	71.4	0	0	10	0	10	0.86	0	3	0.21	0.24	0.00	1.39	0	3.93	3	4.8			
Winter rye	8	3	0	0.5	75.0	0	0	3	0	3	0.25	0	1	0.13	0.52	0.00	0.98	1	5.79	4.5	8.5			
Winter wheat	4	7	0	3.3	25.0	0	0	6	0	7	1.75	0	5	0.81	0.47	0.00	1.44	2	4.75	3	8			

[a] Interventions are the application of a PPP or a mixture of PPPs at a given time (application time).

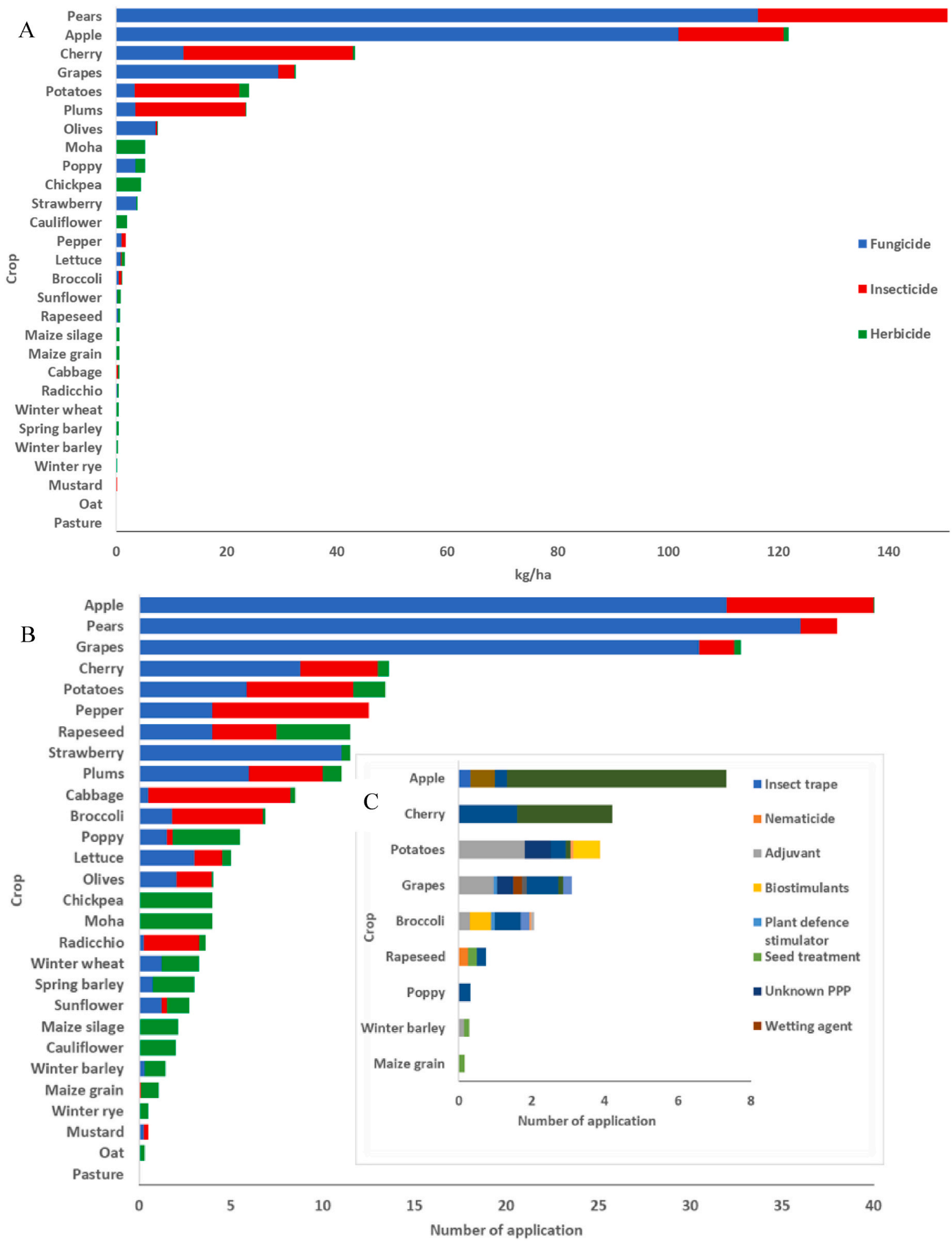

Fig. 2. (A) Overview of cumulative amounts of fungicides, insecticides and herbicides applied per crop in kg/ha. (B) cumulative application of fungicides, insecticides, herbicides at field level and (C) related inputs during cropping season per crop.

herbicides) were applied on the fields in this study during the 2021 season (appendix 3). Sulfur and copper (both fungicides and compliant with organic regulations) are by far the most important PPPs, both in terms of frequency of use and quantities applied (appendix 3). Sulfur was used in 194 applications and copper in 166 applications (appendix 3), respectively (out of 1718 total applications). In terms of average kg/ha doses applied, Equisetum arvense macerate (organic insecticide) was the active substance applied with highest dose 50 kg/ha followed by Mineral oil 45 kg/ha, Kaolin 9 kg/ha and paraffin oil 8 kg/ha (Fig. 3).

Sulfur was used in organic, IPM and conventional farming practices, predominantly in grapevine (21 farms) and fruits (6 farms and 4 vegetables producing farms). In organic farms, frequently used active substance included copper hydroxide (78 applications), sulfur hydroxide (51 applications), use of Bacillus thuringiensis (37 applications), aluminium sulfate (36 applications), paraffin oil (33 applications) and potassium bicarbonate (28 applications). Between 3 and 33 farms used those active substance and if applied, they were applied between 2.75 and 12 times during the cropping season. PPP-based pest control was achieved in organic farms, but also in some IPM and conventional farms by using pyrethrin (17 applications mainly in organic producing farms in grapes and vegetables), granulovirus (14 applications, in organic/IPM/conventional producing farms on fruits), orange oil (13 applications, mainly in organic grape producing farms and in potatoes conventional producing farms), kaolin (12 applications in grapes and olives organic producing farms), azadirachtin (12 applications in vegetables and fruits organic producing farms), and spinosad (9 applications in vegetables and fruits in organic/IPM/conventional producing farms). The other active substance authorized in organic systems were applied between 1 and 6 times during the season. The only active substance compliant with organic farming listed as candidate for substitution is copper (European commission, 2021).

The predominant insecticidal active substance used in conventional and IPM farms were acetamiprid (37 applications in vegetables, fruits, potatoes and oilseed crops), deltamethrin (31 applications in vegetables, grapes and olives) and lambda-cyhalothrin (26 applications in mainly vegetables and potatoes). Less frequently applied insecticidal, fungicidal and herbicidal active substance (i.e. between 13 and 24 applications in the season) included difenoconazole, esfenvalerate and cyazofamid (in potatoes), fosetyl aluminium (in grapes), mandipropamid and cymoxanil (in grapes and potatoes), trifloxystrobin (in grapes, fruits and olives), metalaxyl-M (in grapes and vegetables), glyphosate (in grapes, fruits, olives, potatoes and cereals), tebuconazole (in grapes, cereals and oilseed rape), and mancozeb (mainly in grapes). From the 125 synthetics active substance, 95 were applied more than 2 times during the season. Major type of PPP reported from Argentina were herbicides and main difference between PPP application in European countries and Argentina is that several active substances are currently not authorized in the EU, but used in Argentina, including atrazine (herbicide, 3 applications on maize grain), carbofuran (insecticide-seed treatment, 1 application on maize grain) and paraquat (herbicide, 1 application on chickpea). Several active substances applied during the 2021 season had not received a renewed approval in the EU and could be used due to a grace period allowed by the Member States (CTGB, .). These include thiophanate-methyl (fungicide, 5 applications on cherry and sunflower), thiamethoxam (insecticide-seed treatment, 1 application on maize grain), thiacloprid (insecticide, 1 application on plums), mancozeb (fungicide, 13 applications on grapes, poppy and potatoes), indoxacarb (insecticide, 8 applications on vegetables, grapes and fruits), imidacloprid (insecticide, 4 applications on olives), alpha-cypermethrin, glufosinat-ammonium (herbicide, 5 applications on maize grain and fruits), fenbuconazole (fungicide, 2 applications on grapes) and cyproconazole (fungicide, 1 application on winter barley). Glufosinat-ammonium, imazamox, lambda-cyhalothrin, metalaxyl-M, metconazole, metribuzin, oxamil, pendimethanil, quizalofop-P-ethyl, tebuconazole and thiacloprid are furthermore all candidates for substitution.

The PPP active substance cover a wide range of Modes of Action (MoA) as defined by the FRAC, IRAC and HRAC classification systems (FRAC Committee, ; HRAC Committee, ; IRAC Committee, .; Jeschke et al., 2019; Sparks and Nauen, 2015). Regarding fungicides, active substance used in the CSS include 12 different MoA (Table 3); the most frequently used active substance (sulfur, copper) belong to the group of multi-site MoA. Reported insecticides cover 17 different insecticide MoA (Table 3). The most frequently used insecticides (31.7% applications) belong to the group of sodium channel modulators, followed by 14.9% of the applications with insecticides belonging to the MoA group of nicotinic acetylcholine receptor competitive modulators. Herbicides fall into 16 herbicide MoA categories; the most frequently used herbicides (15.8% of herbicide applications) belong to the auxin mimics MoA group (Table 3). Several active substances used in the CSS are known for showing cross resistance with other molecules (Derpmann and Mehl, 2019.) leading to activity loss. These include e.g. azoxystrobin (fungicide, MoA respiration) used in broccoli, strawberry, grapes, pepper, sunflower, rapeseed, potatoes, mustard, and winter barley (in total applied 20 times), showing cross resistance within the same MoA group with fungicide respiration inhibitors such as boscalid (used in grapes, sunflower, rapeseed (in total used 12 times)), fluopyram (used in grapes, rapeseed, barley, wheat (in total used 5 times)), fluxapyroxad (used in broccoli, grapes, barley (in total used 6 times)), or isofetamid (used once in rapeseed). In appendix 3 it is detailed which active substance are used in organic farming systems.

3.4. Impact of product use recommendations on on-farm application practices

Use of PPPs involves a series of decisions by the farm operator including the decision on which pests/diseases should be controlled, which active substance should be used and when should the product formulations be applied. The intended dosage of an active substance is

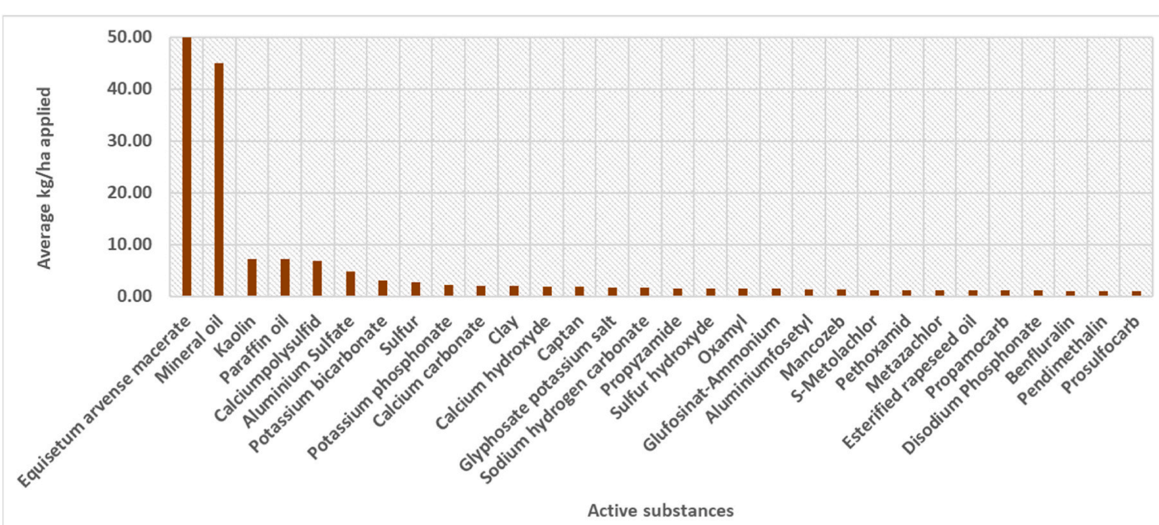

Fig. 3. Average kg/ha of active substances applied across all Case Study Sites during the 2021 season. In this figure the first 30 a.s. most applied are shown (full list of active substances in appendix 3).

Table 3
Percentage of fungicide, insecticide and herbicide active substances categorized by mode of action reported across all considered case study sites. Modes of action are categorized following official FRAC, IRAC, HRAC classifications.

Type of compound	Mode of Action	Percentage of the mode of action used and applied
Fungicides	Nucleic acids metabolism	1.6
	Cytoskeleton and motor protein	3.1
	Respiration	10.2
	Amino acids and protein synthesis	0.1
	Lipid synthesis or transport/ membrane integrity or function	1.9
	Sterol biosynthesis in membranes	5.6
	Cell wall biosynthesis	3.6
	Host plant defence induction	6.5
	Unknown mode of action	2.5
	Multi-site activity	54.7
	Biologicals with multiple modes of action: plant extracts	2.5
	Not specified in FRAC list	7.6
Insecticides	Acetylcholinesterase inhibitors	2.5
	Sodium channel modulators	31.7
	Nicotinic acetylcholine receptor competitive modulators	14.9
	Nicotinic acetylcholine receptor allosteric modulators	2.5
	Glutamate-gated chloride channel allosteric modulators	1.1
	Chordotonal organ modulators	0.8
	Mite growth inhibitors affeting CHS1	0.6
	Microbial disruptors of insect midgut membranes	11.0
	Voltage-dependent sodium channel blockers	2.2
	Inhibitors of acetyl CoA carboxylase	4.1
	Ryanodine receptor modulators	3.0
	Compounds of unknown or uncertain MoA	3.3
	Non-specific mechanical and physical disruptors	4.7
	Contact	8.3
	Ingestion	6.1
	Not specified in IRAC list	2.5
	none	0.8
Herbicides	Inhibition of acetyl CoA Carboxylase	2.3
	Inhibition of Acetolactate Synthase	11.9
	Inhibition of Microtubule Assembly	4.0
	Auxin Mimics	15.8
	Inhibition of photosynthesis at PSII-D1 Serine 264 binders	9.6
	Inhibition of Enolpyruvyl Shikimate Phosphate Synthase	11.9
	inhibition of Glutamine Synthetase	2.8
	Inhibition of Phytoene Desaturase	4.5
	Inhibition of Deoxy-D-Xylulose Phosphate Synthase	2.3
	Inhibition of Protoporphyrinogen Oxidase	8.5
	Inhibition of Very Long Chain Fatty Acids	9.0
	PSI electron diversion	0.6
	Inhibition of Hydroxyphenyl Pyruvate Dioxygenase	9.0
	Inhibition of Solanesyl Diphosphate Synthase	1.7
	Antidote	2.3
	Not specified in HRAC list	4.0

often linked to a specific crop stage, weather situation, or product costs. PPP users are supported by instructions on product labels, technical leaflets and similar information issued by advisory services or companies providing decision support on PPP selection, application timing and dosage recommendations. In this study, we analysed a total of 1718 applications of PPPs and non-PPPs (e.g. adjuvants, fertilizers) involving operators' decisions. For the reported product and crop/pest combinations, 1457 application recommendations were extracted from product technical leaflets (harmonized across countries according to parallel trade), and from the French pesticide database (Anses, https://ephy.anses.fr), and included in our database (https://doi.org/10.5281/zenodo.12526872). In total, 88 PPP recommendations (annex 4) could not be identified for several reasons: product leaflets were not available, reported PPP names could not be found in product database or manufacturer catalogues, some PPPs were reported as active substances and could therefore not be assign to a PPP. More than 60% of the missing PPPs recommendations are fungicides, insecticides or herbicides (annex 4).

Fig. 4 shows the relationship between PPP use recommendations according to the distributor/manufacturer and the applied dosage reported by the farm operator. In Fig. 4A and B we show this relationship respectively for fungicides and insecticides authorized in organic farming, and in Fig. 4C, D and 4E respectively for fungicides, insecticides and herbicides based on synthetic active substances. In general, the data indicate that there is considerable variability and deviation between recommended and applied dose of PPPs. The data suggest that there is also a large proportion of overuse and underuse (PPP applied below recommended dose) of PPPs, resulting in deviations in the order of magnitudes in some cases. Almost all fungicides and insecticides authorized in organic farming are used as recommended or lower applied dose than recommended. For example, sulfur and copper-based PPPs were usually applied below recommendations (e.g. in grapes, sulfur was applied a factor 3 below recommendations and copper up to a factor 20 below recommendations). Their use was mostly applied as a preventive measure against fungal pathogens, which explains underuse of such PPPs, e.g. powdery mildew in grapes. For synthetic PPPs (not authorized in organic farming), the data show a tendency to use lower-than-recommended doses of herbicides, whereas insecticides and fungicides show a tendency to be applied as recommended or above recommended doses. For example, overuse was shown in vegetables, e.g. cabbage applied with Cythrine Max (active substance cypermethrin), as curative treatment was used to a factor 20 above recommended doses. In this case, curative use underlines an already infested field, which might explain overuse of this insecticide.

Finally, we compared use recommendation of one fungicide single Mode of Action (MoA), from the group of respiration and related five target sites (Table 4) to evaluate resistance building risks. We made the comparison for respiration MoA as this was the most used single MoA for fungicide applications (Table 4). Guidelines were collected from FRAC and compared to reported application data at CSS level. We found that all application patterns followed recommendations and applied even less often the single MoA active substance than authorized, excepted for 1 potato farm which applied 1 time more than authorized.

3.5. Costs of plant protection product applications

Crop protection is, among others, driven by economic considerations, i.e. total costs should not exceed benefits associated with prevention of crop yield losses. Expenses for purchase of PPP is an important cost factor. Based on publicly available data and on farm usage, the costs of the whole crop protection strategy, including PPPs and non-PPPs applied per ha and season was assessed (Fig. 5). Year of product purchase was not mentioned by the farmers so we amended product costs based on the 2021 prices in each country of each product and used 2021 currency for price conversion in Argentina. The highest expenses for PPP use were reported in perennial crops, i.e. in apples 3100€/ha/y, pears 2500€/ha/y, and cherry 1800€/ha/y, whereas PPP in grapes cost approximately 1000€/ha/y. In apple, pears, pepper, grapes and strawberries, highest purchase costs were generated due to fungicide use, whereas in cherry, plums, potatoes and broccoli, highest costs were caused by insecticide use. In some vegetables (cauliflower) and cereals (maize, poppy, moha), costs were mainly driven by purchasing applied herbicides.

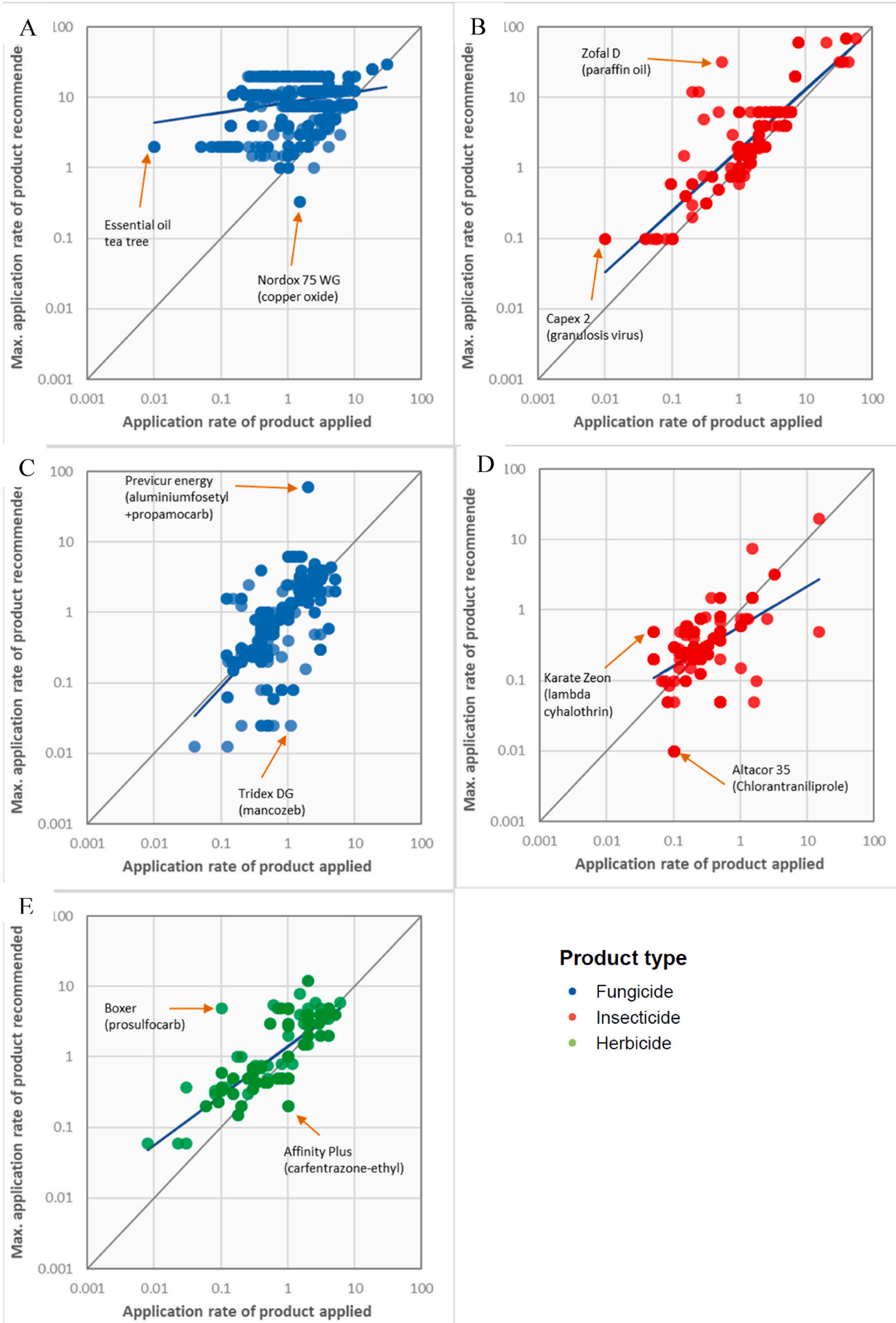

Fig. 4. Correlation between product use recommendations and reported on-farm average dose. (A) correlation for organic fungicides (B) correlation for organic insecticides (C) correlation for synthetic fungicides (D) correlation for synthetic insecticides (E) correlation for synthetic herbicides.

Table 4
Use recommendation of fungicide single Mode of Action (MoA). Targeted MoA is Respiration with 5 target sites. Guidelines were collected from FRAC and compared to reported application data at case study site (CSS) level.

Target site of Respiration Mode of Action	Crops	Guidelines (FRAC)	Reported applications in the CSS
SDHI (boscalid, fluopyram, fluxapyroxad, isofetamid)	Grapes	max. 3 application of SDHI per year	max 3 applications for one farm, then 2 or less
	Vegetables (broccoli)	When 9 applications in total of all PPPs, max. 3 SDHI applications	2 applications
QoI (azoxystrobin, kresoxim-methyl, pyraclostrobin, trifloxystrobin)	Grapes	max. 4 applications of QoI	Max 3 reported
	Oilseed crops	If 12 applications in total of all PPPs, max 4 QoI applications	1 QoI application
C5: uncouplers of oxidative (fluazinam, meptyldinocap)	Strawberry	low risk, used in rotation	2 C5 applications for 12 fungicide applications in total
phosphorylation fluazinam, meptyldinocap)	Grapes	low risk, used in rotation	1 C5 application
Quinone inside Inhibitors (cyazofamid, amisulbrom)	Potatoes	Always apply QII fungicides in mixture with effective partners such as multi-site or other noncross resistant fungicides in high risk countries, max 4	29 applications in total, 5-time QII applied, 3 times together with an unkwon fungicide and 2 times with another type of product
Quinone outside Inhibitor, stigmatellin binding type (Ametoctradin	Grapes	Apply a maximum of 3 applications per season for control of grape downy mildew control. Use always in mixture (ready-mix or tank-mix) with an effective downy mildew partner.	2 applications max accross farms

3.6. PPP use and hazard statements in different farming systems

As explained above, we compared average PPP use across crops without comparing different farming systems. In the present part of the analysis, we tried to point out the differences in PPP use in conventional, IPM and organic farming practices. In appendix 2, we detailed how farms were classified related to their farming practices and the number of farms in each of the farming practices per crop analysed. For this analysis we selected 3 main crop types (fruits, vegetables and cereals). and due to the high number of farms per cropping system we decided to detail the analysis hereafter for fruits as apples (1 IPM, 2 organic) and grapes (5 conventional, 7 IPM, 10 organic), on vegetables as potatoes (5 conventional, 3 IPM, 7 organic) and broccoli (8 conventional, 1 IPM, 7 organic) and on 1 cereal crop as maize silage (7 conventional, 7 organic). In appendix 5, Figs. 1 and 2 detail the analysis for all crops of the eleven case study sites of the study.

First, we compared the average number of applications per crop and farming system (Fig. 6). In apples organic farms performed 37 interventions during the season and IPM farms 48 interventions. In both farming systems, most applied PPPs were fungicides. Grapevine producers in organic farming systems made 42 interventions, IPM farms 25 interventions and conventional farms 35 interventions. In all three farming systems, fungicides were the most applied PPPs. In broccoli, organic farms performed 7 interventions, IPM farms 4 interventions and conventional farms 9 interventions. In all three farming systems, insecticides were the most applied PPPs. In potatoes organic producers did no treatments, IPM farms did 17 interventions and conventional farms 28 interventions. Fungicides and insecticides were the most applied PPPs. In maize silage organic producers did no treatments and conventional farms did 4 herbicide interventions.

In a next step we analysed the average amounts of active substances applied per crop and farming type (Fig. 7). In fruit crops (apple and grapes), the highest quantities of active substances applied were reached in organic practices with 150 kg/ha in apples (average of 2 farms) and 40 kg/ha in grapes (average of 10 farms). Potatoes and maize silage organic production did no treatments and in broccoli 7 kg/ha were applied in organic (average of 7 farms) farming and 10 kg/ha in conventional farming (average of 8 farms).

We then analysed the number of organic (PPPs authorized in organic farming) and synthetic active substances (PPPs not authorized in organic farming) (Table 5) per farming system and per crop type applied. We found that in organic production the variation of active substances applied is smaller than in conventional and IPM production. In conventional and IPM production systems few organic pesticides are used in combination to synthetic pesticides excepted in maize silage where only synthetic herbicides were used. Organic potatoes and maize silage production systems showed no pesticide use. Product application ranges for synthetic pesticides are much lower than organic products (e. g. in apple IPM production lowest rates for synthetic pesticides were 0.08 L/ha against 0.32 L/ha and up to 25.6 L/ha for organic pesticides). Regarding hazard classifications of active substances applied, we showed that conventional and IPM farming systems used up to 24 pesticides (grapes) classified as hazardous whereas organic grape production used 3 pesticides classified as hazardous. In appendix 6 are shown the detailed hazard classifications for each active substance.

3.7. Non-PPP practices as crop protection strategies in different farming scenarios

We showed in our previous analysis of this work the application patterns and differences in PPP use across farming systems and crops. Here we describe the non-PPP practices we identified which lead to decrease pesticide dependency. Again, we focused on 5 selected crops, namely apple, grapes, broccoli, potatoes and maize silage. Data from all considered crops can be found in the database. We identified 4 categories of practices leading to reduce use of PPP (Table 6): crop rotation, use of resistant varieties, use of decision support systems and specific agronomic management practices. Regarding crop rotation, apple and grapes are perennial crops so no rotation was identified. In potatoes, maize silage and broccoli crop rotation seemed to be important in organic systems. Potatoes producers practice long crop rotation by growing potatoes on the same field once every 6 agronomic seasons in organic systems, in IPM systems once every 3 years and no data was reported in conventional systems. Interestingly, organic potato growers used no PPPs (Figs. 6 and 7). Broccoli producers practice longer crop rotations in IPM systems, once every 5 year and once every 3 year in organic systems and only once every 2 ou 3 year in conventional systems. PPP use in this crop showed a higher use of insecticides having hazard statements in conventional farming systems compared to IPM and organic systems (Table 5). Maize silage producers in organic systems practice long crop rotation with growing maize once every 5 year whereas in conventional systems, crop rotation seems to be absent in some farms and some growing maize silage every 2 or 5 years. Regarding use of resistant varieties in apple production, we identified use of scab and firebrand resistant varieties (Topaz, Rubinola and Bonita) in both, IPM and organic systems. All farms seemed to use decision support systems, excepted organic farms for maize silage production.

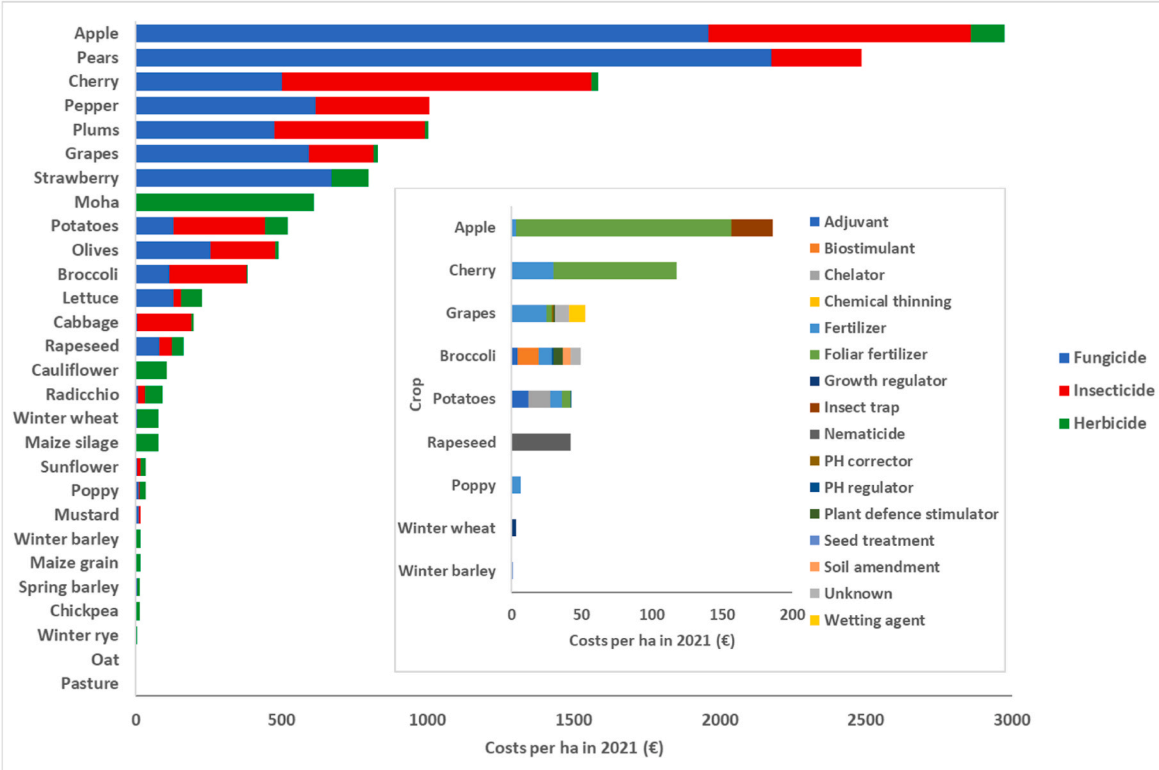

Fig. 5. Costs of plant protection products applied per ha per crop in 2021 across considered case study sites.

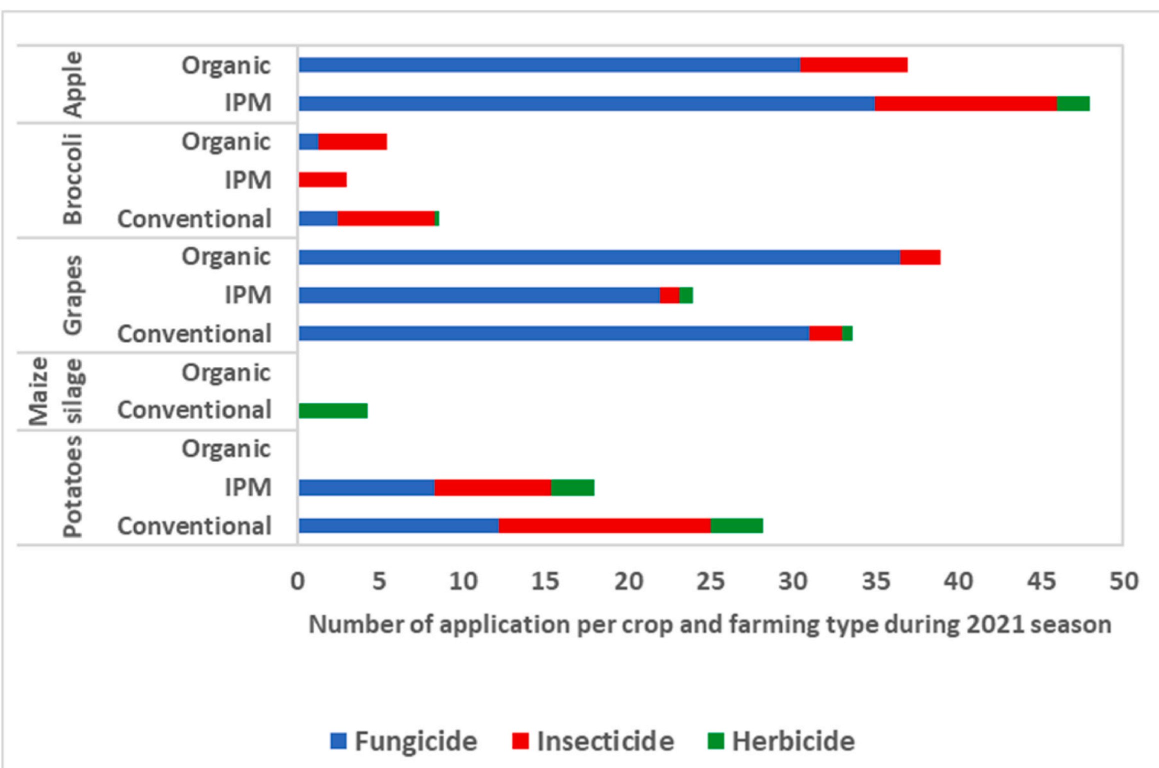

Fig. 6. cumulative application of fungicides, insecticides, herbicides at field level in different farming practices.

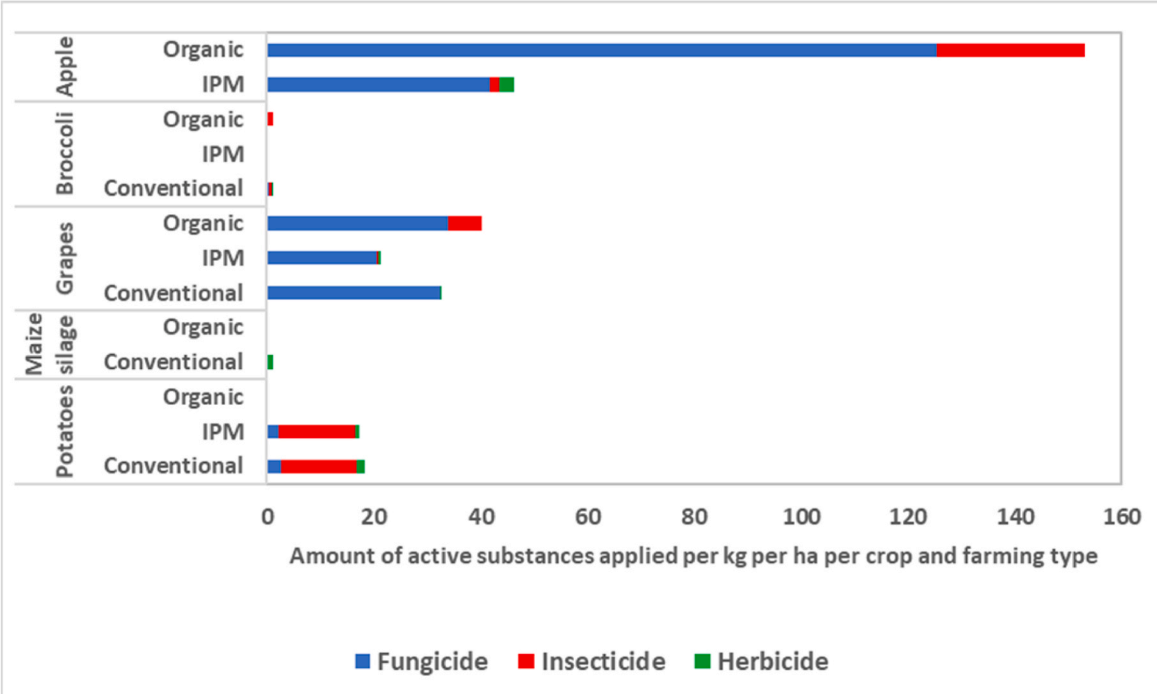

Fig. 7. Overview of cumulative amounts of fungicides, insecticides and herbicides applied per crop in kg/ha per farming practice.

Table 5
Number of active substances applied per crop and farming system, their application ranges and related hazard classifications.

Crops	Farming system	Number of different a.s. applied	Number of organic a.s. applied	Number of synthetic a.s. applied	Range application dose of organic product recommended (kg or L/ha)	Range application dose of synthetic product recommended (kg or L/ha) [a]	Number of organic a.s. with hazard classification[b]	Range of hazard statements per organic a.s[c]	Number of synthetic a.s. with hazard classification[b]	Range of hazard statements per synthetic a. s[c]
Apple	IPM	17	7	10	0.32–12	0.08–5	1	1–2	6	2–6
	Organic	8	8	0	0.1–70	NA	1	1	0	0
Grapes	Conventional	35	9	26	0.3–20	0.0125–8	3	1–5	17	1–6
	IPM	35	3	32	0.5–20	0.05–12	1	1	24	1–9
	Organic	23	23	0	0.75–20	NA	3	1–5	0	0
Potatoes	Conventional	28	3	25	5–6.25	0.25–20	0	0	19	1–6
	IPM	19	2	17	6.25	0.025–6.25	0	0	13	2–6
	Organic	0	0	0	NA	NA	0	0	0	0
Broccoli	Conventional	18	1	17	0.75–3	0.01–2	0	0	12	1–5
	IPM	2	0	2	NA	0.085–0.1	0	0	2	2–5
	Organic	9	9	0	0.2–12	NA	2	2–5	0	0
Maize silage	Conventional	6	0	6	NA	0-44-4	0	0	4	3–5
	Organic	0	0	0	NA	NA	0	0	0	0

[a] The range application dose of organic/synthetic product recommended are the minimum and maximum values of product rates which are given in the product technical leaflets. The lowest number in the table is the lowest application rate for a given product and the highest number is the highest application number for a product.
[b] The number of active substances (a.s.) with hazard classification means how many of the applied a.s. have one or more hazard statements (appendix 5).
[c] considering all active substances having a hazard statements, the range given in this column is the lowest number of hazard statement for an active substance and the highest number of hazard statement (e.g. one active substance can have up to 9 hazard statements in this study).

Interestingly, mechanical weeding once or several time during growing season was only reported for organic producing farms in all crops and therefore no use of herbicides (e.g. maize silage).

4. Discussion

4.1. Variability in PPP applications across considered case study sites

This study comprises a unique dataset on farm-level agronomic practices and plant protection activity patterns during the 2021 season in 11 countries and for 3 crop types (perennial crops, vegetables and cereals). The data reported here represent a certain variability of current farming practices in the season of 2021, which was characterized by generally humid weather conditions throughout Europe (Copernicus, 2021), leading to high pest pressure, except for Argentina, where the rainfall was below the average of the last 50 years (Argentina agriculture, 2021).

Our study included organic, IPM and conventional production systems and comprises more than 1700 application events with usage of more than 170 different active substance Depending on the crop, a wide range of active substance. was used e.g. for grapes (72 different active substance). The diversity of active substance. usage per farm ranged

Table 6
Non-PPP practices for 5 main crops in different farming systems.

Crops	Farming system	Non-PPP farming practices			
		Crop rotation	Resistant varieties	Decision support systems	Agronomic practices
Apple	IPM	no rotation	Bonita, Rubinola (Scab, Fireblight), Topaz (Scab)	Online infos, advisors, weather station	
	Organic	no rotation	Bonita (Scab, Fireblight), Topaz (Scab)	Online infos, advisors, weather station	Mechanical weeding several times during the season
Grapes	Conventional	no rotation	Old varieties, no specific resistances	Advisors, journals, meteo	
	IPM	no rotation	Old varieties, no specific resistances	Advisors, journals, meteo	
	Organic	no rotation	Old varieties, no specific resistances	Advisors, journals, meteo	Mechanical weeding and regular mowing around the plants, organic fertilization
Potatoes	Conventional	no report	no report	Journals, consultants	
	IPM	1:3 once every 3 year or no rotation	no report	Journals, consultants	
	Organic	1:6 potatoes once every 6 year	no report	Non-commercial parties advises, colleagues	Mechanical weeding
Broccoli	Conventional	1:2–1:3 broccoli once every 2 or 3 year	no report	Regular sampling, use of predictive tools	
	IPM	1:5 broccoli once every 5 year	no report	Regular sampling, use of predictive tools	
	Organic	1:3 broccoli once every 3 year	no report	Regular sampling, use of predictive tools	Mechanical weeding
Maize silage	Conventional	3 years in a row, every 2 years or once every 5 year	all hybrids	Alert on pesticide use	
	Organic	1:5 (maize silage once every 5 year)	all hybrids	No decision support system used	Mechanical weeding

from 4 to 21 different active substance. in the 2021 season, indicating the variability in agronomic practices within a given crop. This variability could be explained by many causes, from varieties - hybrids more or less resistant to pests, microclimates where the crops were grown, lack of monitoring and preventive controls (an unsatisfying practice that is deeply rooted in Argentina, because it facilitates the work of 1 person in large areas). As expected, grapes, fruits (apple, pears, cherry, plums) and potatoes were the crops requiring the most intensive pest and disease control activities with most applications and diversity in active substance and product use. Most PPP formulations used over all crops were fungicides (mainly due to highly conducive weather conditions with high humidity).

To achieve adequate crop protection, farmers intensively relied on use of active substance listed as candidates for substitution. In some cases, glufosinate-ammonium and thiacloprid were still used despite their phasing out due to expired authorization.

The majority of active substance were multi-site fungicides, which are favorable to prevent fungicide resistance of pathogens. However, single MoA active substance, which are believed to foster selection of resistant pest/disease populations were also widely used across crops. Especially certain MoA groups (e.g. respiration) observed in this study are known to show cross resistance. The use of active substance as single MoA will lead to resistance problems in the evolution as already shown in other studies (Gisi and Sierotzki, 2008).

There is a substantial gap between the recommended dose usage of PPP and the effective use of product per ha by farmers. We found that product uses deviate substantially from product use recommendations. Overdosing active substance may lead to increased exposure and environmental problems. However, underdosing may also cause substantial problems if the practices e.g. lead to the selection of resistant weed, pest and disease populations. It is a recurring agricultural practice that some farmers apply pesticides that are not authorized for the species or crop where they apply it. This is called diversion or unauthorized use, but it does not mean that a prohibited product was applied. It means that for economic reasons, bad advice, lack of knowledge, the pesticide that was available at that time was used, which is authorized for another species. This problem is present in Europe and Argentina (Renspa,).

Rentability of a crop is reached when costs do not exceed crop yield benefits. In our study we collected data on PPP costs and tried to collect real life data on agronomic management costs by asking farmers how many hours they spend for each field activity on that specific crop, and how many expenses they have for each material and machinery use. In parallel we tried to figure out crop benefits. The level of detail we asked for could not be satisfied to make clear statements of crop rentability for each CSS. Also, in costs, environmental costs of pesticide use on human and ecosystem health should be included in true comparison against benefits (Steingrímsdóttir et al., 2018b).

We analysed differences in PPP applications in conventional, organic and IPM farming systems. Although data show that organic farms usually use higher amounts of PPPs and sometimes higher PPP interventions than conventional and IPM farms, we note that application rates are higher (up to 100-fold) for PPPs authorized in organic production. Synthetic pesticides are applied with much lower rates and are classified, for most of them as hazardous. For example, in grape production 24 out of 32 active substances are classified as hazardous pesticides, showing between 1 and 9 different hazard classifications each. This is in line with the analysis of hazard statements of active substances across conventional and organic farming described by Burtscher-Schaden et al. (2022). PPP use intensity varies substantially between individual farms within the same region, in some cases at similar yield levels. This indicates that there is potential for reducing pesticide use in such cases without decrease in crop yields, in line with other studies (Lechenet et al., 2017). Our dataset revealed that the contribution and potential of using preventive agronomic practices such as crop rotation or robust cultivars combined to decision support systems lead to reduction of the dependency on PPP use. In Table 7 we listed strategies we could observe in our analysis to reduce PPP use.

4.2. Limitations of the proposed data and followed approach

Data collection was performed by CSS teams, and the quality of data was dependent on the willingness of farmers to be as specific as possible when answering the questionnaire. The crops were strategically selected to represent climatic zones of the respective CSS and importance of the crop in each country in terms of production. While the data gives an overview of the situation within a region, extrapolations to other pedoclimatic zones may not be appropriate. To obtain a comprehensive overview of current pest control practices, further countries need to be

Table 7
Strategies to reduce PPP use and synthetic pesticides collected at farm level in the case study sites.

Type of crops	Preventive measures to reduce PPP use	Replacement of synthetic PPP through organic PPP
Perennial crops (e.g. apple)	Weather station, regional advisor support, damage thresholds, Phytosanitary notices, online information, use of resistant varieties (e.g. Topaz: scab resistance)	Myco-Sin, NeemAzal T/S, Curatio, Madex Top
Grapevine	Warning systems at wine station, monitoring observation, resistant cultivars which are adapted to the region, weather prognostics, advisor support, regional bulletins	Kumulus S, Heliosoufre S, Bouillie bordelaise, Thiovit Jet
Cereals	Notifications, newsletter, farmers associations, resistant varieties, optimal sowing date, 4-year crop rotation	Some farms did no treatments, and strategy was set on preventive measures.
Potatoes	Following non-governmental own paths, non-commercial instructions, crop rotation	Some farms did no treatments and strategy was set on preventive measures
Vegetables (e.g. broccoli)	Warning systems, periodic visual diseases and pest sampling, advisor support, weather station, use of regional bulletins, crop rotation	NeemAzal T/S, Capsanem, Cuprotect, Prev Am

included to complement our database. Our data is probably not representative for e.g. chickpea, pears, plums with only one farm participating in the survey. Finally, our database contains a high number of organic farms, which is not representative when compared to the proportion of organic farms and conventional farms in real-life. However, this analysis aims to support a transition toward sustainable practices, hence we have put a higher emphasis on including organic farms. Argentina was selected as first rough cross-evaluation of practices outside the European scope, and it would be necessary to include more data from countries outside of Europe to expand and improve the development of novel practice strategies at a global level.

Our approach allows for a very detailed analysis of pest control practices and motivations and thus a thorough understanding of the specific situation. Data collection was carried out in the year of 2021 and due to high humidity and medium temperatures (more wet days than average (Copernicus, 2021) this year is considered as a typical risk year for crops in terms of pest and diseases, where a good cropping strategy is key to maintain good yield performance. In the EU in 2021 a total of 355 000 tonnes of pesticides were sold (European Union Law, 2022) and the cultivated area for arable land was 97.8 million ha and permanent crops 11 million ha (European commission, 2021). In our study we covered 794 ha of cultivation and 1900 kg/ha of pesticide use.

Despite the mentioned limitations, we regard our study to be a useful starting point for deriving a systematic inventory of farm-level pest control in various EU countries.

4.3. Future research needs (and global pest control trends)

We show that high number of applications are still performed with copper-based pesticide products although they are not approved active substance by the EU. Some of the used applications are also listed as candidates for substitution in the EU, such as metconazole and cyproconazole. To identify and evaluate viable pesticide reduction strategies and alternatives of production to reduce use of hazard PPPs and PPP use in general, our data need to be combined with best practices including use of preventive measures (e.g. Table 3 mentioned above) and upscale those practices to a large number of farms. Additional research is required to assess one crop type in several regions and countries to explore in detail the panel of different practices and try to identify best practices as function of local environmental and market conditions.

Despite the high public interest in reducing the risks associated with pesticide use, only very limited data is currently available as open source and with the sufficient level of detail. For now, only pesticide sale data per year is available. Even though such data of pesticide use is pivotal in understanding current PPP uses and support the monitoring of the impact of agricultural policies and other pesticide reduction efforts, such data analysis provided by farmers will also have its limitations. Understanding and quantifying the impact of agroecological farming methods on preventing crop losses due to noxious organisms and its contribution to pesticide use reduction will be essential to foster acceptance among farmers and to justify policy support where necessary. The combination of individual data on agronomic practices, pesticide use, economy, and availability of (independent) advisory services allows for the identification of advanced farming systems with successful, economically viable crop production systems. The CSS farm data are a first step towards the thorough understanding of the success factors and another step for understanding the limitations of current best farming practices and the potential for upscaling best practices. Our data suggest that the quantities of PPP used do not correlate well with recommendations. The factors contributing to this discrepancy should be well understood and analysed. Reasons may include lack of information by farmers or, in the contrary, informal information available to farmers, which is not incorporated in official documentation. This adds to the information gap related to (i) the availability and affordability of precision-farming techniques and less hazardous alternatives to chemical pesticides and (ii) the lack of evidence on pesticide sales and use (Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the sustainable use of plant protection products and amending Regulation (EU) 2021/2115). As there is an urgent need to broaden our understanding of current plant protection strategies at farm level, upscaling the CSS survey to include more regions, crops and pesticides is required.

5. Conclusions

This study provides a detailed insight on how crop protection in EU countries is performed across a large set of individual farms, and which pesticides are used during a complete season in different cropping systems. We get insights in different conventional/IPM/organic farming practices and related PPP use. We found that there is contrast within and between crops regarding PPP application practices in terms of application timings, number of applications, type and frequency of product used. We found that most pesticides were applied in grapes (France and Portugal), potatoes (Netherlands) and broccoli (Spain) and highest mass per ha of pesticides were applied in perennial crops: apples, pears and cherry in Switzerland and grapes in France and Portugal. Across all active substances applied, 12% are candidates for substitution and 5.6% are not renewed. We analysed cropping systems in 10 countries and 28 crops in Northern, Central and Southern Europe, which includes most important crops in this area and cereal production in Argentina. This study can be used to help and support pesticide use reduction of moving toward more sustainable use of pesticides in Europe as we made a detailed state of the art of current practices in terms of pesticide use and application.

CRediT authorship contribution statement

Jennifer Mark: Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Peter Fantke:** Writing – original draft, Methodology, Conceptualization. **Farshad Soheilifard:** Writing – review & editing, Investigation. **Francisco Alcon:** Writing – review & editing, Investigation. **Josefa Contreras:** Writing – review & editing, Investigation. **Nelson Abrantes:** Writing – review & editing, Investigation. **Isabel Campos:** Writing – review & editing, Investigation. **Isabelle Baldi:** Writing – review & editing, Investigation. **Mathilde Bureau:** Writing – review & editing, Investigation. **Abdallah Alaoui:** Writing – review & editing, Investigation. **Florian Christ:** Investigation. **Daniele Mandrioli:** Writing – review & editing, Investigation. **Daria Sgargi:** Writing – review & editing, Investigation. **Igor Pasković:** Writing – review & editing, Investigation. **Marija Polić Pasković:** Writing – review & editing, Investigation. **Matjaž Glavan:** Writing – review & editing, Investigation. **Jakub Hofman:** Writing – review & editing, Investigation. **Paula Harkes:** Writing – review & editing, Investigation. **Esperanza Huerta Lwanga:** Writing – review & editing, Investigation. **Trine Norgaard:** Writing – review & editing, Investigation. **Virginia Aparicio:** Writing – review & editing, Investigation. **Vivi Schlünssen:** Writing – review & editing, Investigation. **Anne Vested:** Writing – review & editing, Investigation. **Vera Silva:** Methodology, Investigation. **Violette Geissen:** Methodology, Funding acquisition, Conceptualization. **Lucius Tamm:** Writing – original draft, Supervision, Methodology, Data curation, Conceptualization.

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

Data are uploaded on zenodo and can be accessed via https://doi.org/10.5281/zenodo.12526872.

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Appendix 1. Data recovery from data collection

Between 10 and 19 farms were selected per Case Study Site (CSS) and asked to participate to the interview. Questionnaires were filled in by CSS Teams. In appendix Table 1 and it is shown how many farms finally provided answers to questionnaires. In total, 135 farms provided useable data out of 144 initially selected. From the 9 farms which were not included in the study, 5 never answered to the interview and 4 (CSS 4) did not provide sufficient detailed data to be included in the study (e.g. incomplete pesticide records). After the interview, data collected was checked for completeness and plausibility. Each farm information, application date, product, agronomic management practice was verified. In Table 1 it is shown which data per CSS were missing or incomplete. In all CSS the most incomplete and difficult data to be provided by farmers were the costs and benefits of the crop on the reference fields analysed. Therefore, we did not include this part in the study and data was used for other purposes within the project and complemented by expert workshops to collect necessary data. Another incomplete data was details on BBCH stage of the crops. For CSS 3 (grapevine in France), CSS 4 (fruits in Switzerland) data could be collected through regional publications (BSV, 2021; Schweizerische Eidgenossenschaft, 2021) where such data is provided. Proxies were made for CSS9 (potatoes in Netherlands) and CSS2 (grapevine in Portugal) where data could be collected through publications in other countries/regions (potatoes in Est France, and grapevine in South France) as climatic conditions and sowing dates of potatoes where in line with the CSS.

Regarding pesticide use, we collected leaflets from all products which were applied in all CSS and used them for details on product composition (e.g. active substances of each product and amount of active substance). Sources of product costs were on one hand provided by farmers in each CSS, found in publicly available literature or websites: livre France, Suisse. On the other hand, some proxies were generated for product costs were none details could be found for the product sale in the CSS precisely. Proxies were generated by taking product costs in another country (2% of the products in the study).

Finally, all the dataset was complemented by other data sources, as shown in Table 1. It included EPPO codes for pests and diseases, Mode of Action (MoA) of active substances, product recommendations (collected from product leaflets).

Table 1
Data recovery and quality of responses per Case Study Site

CSS	CSS1	CSS2	CSS3	CSS4	CSS5	CSS6	CSS7	CSS8	CSS9	CSS10	CSS11
Number of farms asked for filling in the questionnaires	12	10	13	12	11	19	12	13	16	12	14
Number of farms kept in the study	12	10	10	8	11	18	12	13	15	12	14
Type of data missing	Some farm details, application technics (speed, nozzles), some product details, BBCH, complete costs-benefits of crop studied	Costs of products, application technics (speed, nozzles), for 2 farms PPP application volumes, some product details, BBCH, complete costs-benefits of crop studied	No data for 3 farms, application technics (speed, nozzles), some product details, dates of activities, BBCH, complete costs-benefits of crop studied	Farm details, no complete PPP records for 3 farms, application technics (speed, nozzles, spray volume), agronomic management practices, BBCH, complete costs-benefits of crop studied	Some farm details, application dates for 2 farms, some product details, some volume of application, BBCH, name of varieties, complete costs-benefits of crop studied	Compliance-certifications of some farms, some product costs, BBCH, complete costs-benefits of crop studied	Some farm details, application technics (speed, nozzles, spray volume), BBCH, complete costs-benefits of crop studied	Region of farms, farm details, some product details, technic of application (speed, nozzles), BBCH, some uncertainties in PPP application, complete costs-benefits of crop studied	Farm details for 2 farms, complete information missing for 1 farm, BBCH, application technics (speed, type of nozzles), potatoes varieties, fertilization dates, complete costs-benefits of crop studied products, some agronomic management practices dates	some product details, technic of application for 2 farms, complete costs-benefits of crop studied	Some crop info (crop rotation), BBCH, no PPP data for 4 farms, application technics (Speed, nozzles), dates of agronomic management practices, complete costs-benefits of crop studied
Type of data missing after gap filling	BBCH, complete costs-benefits of crop studied	BBCH, complete costs-benefits of crop studied	No data for 3 farms, dates of some activities, BBCH, complete costs-benefits of crop studied	no complete PPP records for 3 farms, some application technics (speed, nozzles, spray volume), some agronomic management practices, BBCH, complete costs-benefits of crop studied	Name of some varieties, BBCH, complete costs-benefits of crop studied	BBCH, complete costs-benefits of crop studied	BBCH, complete costs-benefits of crop studied	technic of application (speed, nozzles), some BBCH, complete costs-benefits of crop studied	1 complete farm, BBCH, complete costs-benefits of crop studied	BBCH, complete costs-benefits of crop studied	BBCH, complete costs-benefits of crop studied
Type of data amended	EPPO-codes for pest and diseases, mode of action of active substances	EPPO-codes for pest and diseases, mode of action of active substances	EPPO-codes for pest and diseases, BBCH (ref BSV), mode of action of active substances	EPPO-codes for pest and diseases, BBCH, mode of action of active substances	EPPO-codes for pest and diseases, mode of action of active substances	EPPO-codes for pest and diseases, mode of action of active substances	EPPO-codes for pest and diseases, mode of action of active substances	EPPO-codes for pest and diseases, mode of action of active substances	EPPO-codes for pest and diseases, mode of action of active substances	EPPO-codes for pest and diseases, mode of action of active substances	EPPO-codes for pest and diseases, mode of action of active substances

Appendix 2. Description of farming systems

Organic farming system: in this study organic farming systems are farms practicing only organic production by applying PPP authorized in organic production or using no PPP at all.

Integrated Pest Management (IPM): in this study IPM farms are using PPPs in a curative way if possible and only preventive if necessary. Those farms can use both PPPs, organic and synthetic. Allocation to this farming system was communicated by farmers themselves during interview and data collection.

Conventional farming system: in this study conventional farms use mainly synthetic PPP, exceptionally they can also apply an organic PPP. Usually they use PPPs in a preventive way.

In transition to organic: this allocation was communicated by farmers during interview, as they little by little will convert from an IPM or conventional system to an organic production system. At the time of the interview they were not certified organic.

Others: Farms which practice several farming systems (e.g. conventional and organic) dependent on the crop produced. This was mainly the case in Czech Republic.

Table 1
Number of farms in each farming system

Crop	Production system	Number field
Apple	IPM	1
	Organic	2
Broccoli	Conventional	8
	IPM	1
	Organic	7
Cabbage	IPM	1
	Organic	3
Cauliflower	IPM	1
Cherry	Conventional	2
	IPM	1
	Organic	2
Chickpea	Conventional	1
Grapes	Conventional	5
	IPM	7
	Organic	10
Lettuce	IPM	1
	Organic, IPM	1
Maize grain	Conventional	4
	Organic	8
Maize silage	Conventional	7
	Organic	7
Moha	Conventional	1
Mustard	Organic	4
Oat	Conventional	1
	Conventional, in transition to organic	1
	Organic	5
Olives	Conventional	5
	Conventional, in transition to organic	1
	IPM	5
	Organic	8
Pasture	In transition to organic	1
Pears	Organic	1
Pepper	Conventional, IPM	1
	Organic	1
Plums	Conventional	2
Poppy	Conventional, IPM	1
	Organic	1
Potatoes	Conventional	5
	IPM	3
	Organic	7
Radicchio	IPM	3
	Organic	4
	Organic, IPM	1
Rapeseed	Conventional	1
	Conventional, IPM	2
	Conventional, Organic	1
Spring barley	Conventional	4
Strawberry	Conventional	1
	Organic	1
Sunflower	Conventional	1
	Conventional, IPM	1
	Conventional, Organic	1
	Organic	1
Winter barley	Conventional	2
	Conventional, in transition to organic	1
	Organic	4
Winter rye	Conventional	3
	Organic	5
Winter wheat	Conventional	3
	Conventional, in transition to organic	1

Appendix 3. active substances used and applied over all crops and CSS

For each active substance the number of applications over all CSS were reported and average kg active substance per ha per application was calculated across all Case Study Sites applications over the 2021 cropping season.

Active substances	kg/ha	Application number	Number of fields	kg a.s/ha/ application	If applied, how often	Number of products	A.s. Registration EU	Candidate for substitution (draft list 2015 EU)	Use in organic	Bio control agents (microO)	Semiochemicals
2.4-dichlorophenoxyacteic acid	0.3756	6	6	0.06	1.00	3	December 31, 2030	no	no	no	no
Abamectin	0.0396	2	2	0.02	1.00	1	April 30, 2023	no	no	no	no
Acetamiprid	2.619	37	15	0.07	2.47	10	February 28, 2033	no	no	no	no
Aclonifen	0.5	3	3	0.17	1.00	1	July 31, 2023	yes	no	no	no
Alpha cypermethrin	0.1503	7	4	0.02	1.75	3	June 07, 2021	no	no	no	no
Aluminium Sulfate	171.6	36	3	4.77	12.00	1	August 31, 2024	no	yes	no	no
Aluminiumfosetyl	29.689965	22	10	1.35	2.20	8	April 30, 2023	no	no	no	no
Ametoctradin	0.6918	3	2	0.23	1.50	2	July 31, 2023	no	no	no	no
Aminopyralid	0.1454	2	2	0.07	1.00	2	December 31, 2024	no	no	no	no
Amisulbrom	0.1	1	1	0.10	1.00	1	September 30, 2024	no	no	no	no
Atrazine	0.36	3	2	0.12	1.50	1	not approved	no	no	no	no
Azadirachtin	0.37612	12	6	0.03	2.00	2	August 31, 2024	no	yes	no	no
Azoxystrobin	5.686	20	13	0.28	1.54	9	December 31, 2024	no	no	no	no
Bacillus amyloliquefaciens MBI600	0	2	2	0.00	1.00	1	September 16, 2026	no	yes	yes	no
Bacillus amyloliquefaciens plantarum	0	1	1	0.00	1.00	1	March 31, 2025	no	yes	yes	no
Bacillus thuringiensis	4.732	37	9	0.13	4.11	8	April 30, 2023	no	yes	yes	no
Bacillus thuringiensis var. kurstaki, SA12	0.09	5	1	0.02	5.00	1	April 30, 2023	no	yes	yes	no
Beauveria bassiana strain ATCC 74040	0.0000185	1	1	0.00	1.00	1	April 30, 2023	no	yes	yes	no
Benfluralin	1.08	1	1	1.08	1.00	1	February 12, 2023	no	no	no	no
Benthiavalicarb	0.084	3	1	0.03	3.00	2	July 31, 2023	no	no	no	no
Boscalid	0.94985	12	8	0.08	1.50	4	July 31, 2023	no	no	no	no
Calcium carbonate	10	5	1	2.00	5.00	1	October 31, 2036	no	yes	no	no
Calcium hydroxyde	3.88	2	1	1.94	2.00	1	undetermined	no	yes	no	no
Calciumpolysulfid	34.2	5	1	6.84	5.00	1	August 31, 2024	no	yes	no	no
Captan	23.04	12	3	1.92	4.00	2	July 31, 2023	no	yes	no	no
Carbofuran	0	1	1	0.00	1.00	1	not approved	no	no	no	no
Carfentrazone	0.18	2	3	0.09	0.67	1	July 31, 2033	no	no	no	no
Carfentrazone-ethyl	0.1305	3	3	0.04	1.00	2	July 31, 2033	no	no	no	no
Chlorantraniliprole	0.355	11	7	0.03	1.57	2	December 31, 2024	no	no	no	no
Chlorotoluron	0.75	2	2	0.38	1.00	1	October 31, 2023	yes	no	no	no
Clay	2	1	1	2.00	1.00	1	undetermined	no	yes	no	no
Clethodim	0.096	1	1	0.10	1.00	1	May 31, 2023	no	no	no	no
Clomazone	0.1692	4	4	0.04	1.00	2	October 31, 2023	no	no	no	no
Clopyralid	0.192	2	2	0.10	1.00	2	September 30, 2036	no	no	no	no
Coffee	0	1	1	0.00	1.00	1	undetermined	no	yes	no	no
Copper	68.2245	166	33	0.41	5.03	15	December 31, 2025	yes	yes	no	no
Copper hydroxyde	18.27976	78	11	0.23	7.09	7	December 31, 2025	yes	yes	no	no
Copper oxide	5.70525	25	7	0.23	3.57	3	December 31, 2025	yes	yes	no	no
Copper oxychloride	16.26207	23	15	0.71	1.53	5	December 31, 2025	yes	yes	no	no
Copper sulfate	2.84489	6	2	0.47	3.00	2	December 31, 2025	no	yes	no	no
COS-OGA	0.0353125	2	2	0.02	1.00	2	April 24, 2030	no	yes	no	no
Cyazofamid	1.8054	22	9	0.08	2.44	2	July 31, 2036	no	no	no	no
Cyflufenamid	0.12115	6	4	0.02	1.50	4	March 31, 2024	no	no	no	no

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Active substances	kg/ha	Application number	Number of fields	kg a.s/ha/ application	If applied, how often	Number of products	A.s. Registration EU	Candidate for substitution (draft list 2015 EU)	Use in organic	Bio control agents (microO)	Semiochemicals
Cymoxanil	3.8069	20	12	0.19	1.67	7	August 31, 2023	no	no	no	no
Cypermethrin	0.3292	3	3	0.11	1.00	3	January 31, 2029	no	no	no	no
Cyproconazole	0.032	1	1	0.03	1.00	1	May 31, 2021	yes	no	no	no
Deltamethrin	0.654085	31	17	0.02	1.82	10	October 31, 2023	no	no	no	no
Dicamba	0.0864		2	#DIV/0!	0.00	1	December 31, 2023	no	no	no	no
Difenoconazole	1.73685	24	12	0.07	2.00	7	December 31, 2023	yes	no	no	no
Diflufenican	0.275	7	7	0.04	1.00	2	December 31, 2023	yes	no	no	no
Dimethenamid-P	0.72	1	1	0.72	1.00	1	August 31, 2034	no	no	no	no
Dimethomorph	3.70035	13	9	0.28	1.44	7	July 31, 2023	no	no	no	no
Dimoxystrobin	0.2	2	2	0.10	1.00	1	January 31, 2024	yes	no	no	no
Disodium Phosphonate	3.314	3	2	1.10	1.50	2	January 31, 2026	no	no	no	no
Dithianon	9.212	15	5	0.61	3.00	2	August 31, 2024	no	no	no	no
Dodine	0.816	1	1	0.82	1.00	1	August 31, 2024	no	no	no	no
Dust	0.44	22	2	0.02	11.00	1		no	yes	no	no
Emamectin benzoate	0.0608	2	1	0.03	2.00	1	45626	no	no	no	no
Equisetum arvense	0	4	1	0.00	4.00	1	undetermined	no	yes	yes	no
Equisetum arvense macerate	100	2	1	50.00	2.00	1	undetermined	no	yes	yes	no
Esfenvalerate	0.48125	23	4	0.02	5.75	3	45291	no	no	no	no
Essential oil lavender	0.77	3	1	0.26	3.00	1		no	yes	no	no
Essential oil tea tree	2.03	4	1	0.51	4.00	1		no	yes	no	no
Esterified rapeseed oil	3.368	3	3	1.12	1.00	1		no	yes	no	no
Eugenol	0.128	1	1	0.13	1.00	1	45260	no	yes	no	no
Fenbuconazole	0.075	2	2	0.04	1.00	1	April 30, 2021	no	no	no	no
Flonicamid	0.0235	3	3	0.01	1.00	1	August 31, 2023	no	no	no	no
Florasulam	0.001	2	2	0.00	1.00	1	December 31, 2030	no	no	no	no
Florpyrauxifen-benzyl	0.0134	1	1	0.01	1.00	1	July 24, 2029	no	no	no	no
Fluazifop-P-butyl	0.4	2	2	0.20	1.00	2	December 31, 2023	no	no	no	no
Fluazinam	0.75	2	1	0.38	2.00	1	February 29, 2024	no	no	no	no
Fluopicolide	1.406262	15	10	0.09	1.50	4	May 31, 2023	no	no	no	no
Fluopyram	0.3165	5	5	0.06	1.00	3	January 31, 2024	no	no	no	no
Flupyradifurone	0	1	1	0.00	1.00	1	December 09, 2025	no	no	no	no
Flurochloridone	0.425	1	1	0.43	1.00	1	May 31, 2023	no	no	no	no
Fluroxypyr	0.2275	6	4	0.04	1.50	2	December 31, 2024	no	no	no	no
Fluxapyroxad	0.36498	6	4	0.06	1.50	3	May 31, 2025	no	no	no	no
Folpet	10.035	16	7	0.63	2.29	7	July 31, 2023	no	no	no	no
Foramsulfuron	0.21	4	4	0.05	1.00	1	May 31, 2035	no	no	no	no
Gamma-cyhalothrin	0.0288	6	5	0.00	1.20	2	March 31, 2025	no	no	no	no
Geraniol	0.256	1	1	0.26	1.00	1	November 30, 2023	no	yes	no	no
Gliocladium catenulatum	0	1	1	0.00	1.00	1	March 31, 2034	no	yes	yes	no
Glufosinat-Ammonium	2.97	5	3	0.59	1.67	2	July 31, 2018	yes	no	no	no
Glyphosate	10.71339	15	13	0.71	1.15	11	December 15, 2023	no	no	no	no
Glyphosate potassium salt	12.22714	7	4	1.75	1.75	1		no	no	no	no
Granulosis virus	0	14	5	0.00	2.80	3	45046	no	yes	yes	no
Halauxifen-methyl	0.1396	5	3	0.03	1.67	3	August 05, 2025	no	no	no	no
Helicoverpa armigera NPV	0	1	1	0.00	1.00	1	May 31, 2023	no	yes	yes	no
Hexythiazox	0.1	2	1	0.05	2.00	1	August 31, 2024	no	no	no	no
Imazamox	0.0464	1	1	0.05	1.00	1	January 31, 2025	yes	no	no	no
Imidacloprid	0.16	4	2	0.04	2.00	1	December 01, 2020	no	no	no	no

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Active substances	kg/ha	Application number	Number of fields	kg a.s/ha/ application	If applied, how often	Number of products	A.s. Registration EU	Candidate for substitution (draft list 2015 EU)	Use in organic	Bio control agents (microO)	Semiochemicals
Indoxacarb	0.4092	8	7	0.05	1.14	2	December 19, 2021	no	no	no	no
Iodosulfuron-Methyl-Natrium	0.009	1	1	0.01	1.00	1		no	no	no	no
Isofetamid	0.16	1	1	0.16	1.00	1	46280	no	no	no	no
Isoxadifen-ethyl	0.088	4	2	0.02	2.00	1	not assessed yet at EU level	no	no	no	no
Isoxaflutole	0.38925	4	4	0.10	1.00	1	49156	no	no	no	no
Kaolin	87.4	12	4	7.28	3.00	3	August 31, 2023	no	yes	no	no
Kresoxim-methyl	1.375	16	10	0.09	1.60	3	December 31, 2024	no	no	no	no
Lambda-cyhalothrin	0.5974	26	14	0.02	1.86	6	March 31, 2024	yes	no	no	no
Laminarin	0.0675	2	1	0.03	2.00	1	February 20, 2033	no	yes	no	no
Mancozeb	16.534	13	9	1.27	1.44	7	January 04, 2021	no	no	no	no
Mandipropamid	3.75	22	9	0.17	2.44	5	July 31, 2023	no	no	no	no
Mepiquatchlorid	0.231	1	1	0.23	1.00	1	February 29, 2024	no	no	no	no
Meptyldinocap	0.14	1	1	0.14	1.00	1	March 31, 2025	no	no	no	no
Mesosulfuron-Methyl	0.00135	1	1	0.00	1.00	1	June 30, 2032	no	no	no	no
Mesotrione	0.7899	8	8	0.10	1.00	2	May 31, 2032	no	no	no	no
Metalaxyl-M	7.266	17	11	0.43	1.55	8	May 31, 2035	yes	no	no	no
Metaldehyd	0.1428	1	1	0.14	1.00	1	May 31, 2023	no	no	no	no
Metazachlor	4.625	4	4	1.16	1.00	3	July 31, 2023	no	no	no	no
Metconazole	0.264	6	4	0.04	1.50	5	April 30, 2023	yes	no	no	no
Methylated oil	0	1	1	0.00	1.00	1		no	no	no	no
Metiram	10.855402	11	7	0.99	1.57	8	45322	no	no	no	no
Metobromuron	3.65	4	4	0.91	1.00	1	December 31, 2024	no	no	no	no
Metrafenone	0.3975	4	4	0.10	1.00	2	April 30, 2023	no	no	no	no
Metribuzin	0.852	4	4	0.21	1.00	1	July 31, 2023	yes	no	no	no
Milk	0	4	1	0.00	4.00	1	undetermined	no	yes	no	no
Mineral oil	134.64	3	3	44.88	1.00	1	45291	no	yes	no	no
none	0	40	9	0.00	4.44	6		no	no	no	no
Orange oil	1.4148	13	8	0.11	1.63	4	45504	no	yes	no	no
Oregano	0	1	1	0.00	1.00	1		no	yes	no	no
Oxamyl	1.5	1	1	1.50	1.00	1	45230	yes	no	no	no
Oxathiapiprolin	0.056	4	2	0.01	2.00	3	March 03, 2027	no	no	no	no
Paraffin oil	239.9161	33	12	7.27	2.75	5	December 31, 2023	no	yes	no	no
Paraquat	0.552	1	1	0.55	1.00	1	not approved	no	no	no	no
Penconazole	0.29161	8	5	0.04	1.60	3	45291	no	no	no	no
Pendimethalin	3.185	3	3	1.06	1.00	1	November 30, 2024	yes	no	no	no
Pethoxamid	2.34	2	2	1.17	1.00	2	November 30, 2033	no	no	no	no
Pheromons	0	1	1	0.00	1.00	1	August 30, 2037	no	yes	no	yes
Phosmet	3.68	7	6	0.53	1.17	1	February 01, 2022	no	no	no	no
Picloram	1.608	5	4	0.32	1.25	2	December 31, 2023	no	no	no	no
Pine terpenic polymers	0			#DIV/0!	#DIV/0!						
Pirimicarb	0.25	1	1	0.25	1.00	1	April 30, 2023	no	no	no	no
Potassium bicarbonate	85.274	28	6	3.05	4.67	3	June 31, 2036	no	yes	no	no
Potassium phosphonate	32.67641	15	4	2.18	3.75	3	46053	no	yes	no	no
Propamocarb	8.85	8	6	1.11	1.33	4	July 31, 2023	no	no	no	no
Propamocarb hydrochloride	7.1875	9	4	0.80	2.25	1		no	no	no	no
Propaquizafop	0.1	1	1	0.10	1.00	1	45260	no	no	no	no
Propyzamide	4.8	3	3	1.60	1.00	2	June 30, 2025	no	no	no	no
Prosulfocarb	6.28	6	6	1.05	1.00	2	October 31, 2023	no	no	no	no
Prothioconazole	0.35935	5	5	0.07	1.00	3	July 31, 2023	no	no	no	no
Pyraclostrobin	0.21005	4	3	0.05	1.33	3	January 31, 2024	no	no	no	no
Pyraflufen-ethyl	0.17182	8	6	0.02	1.33	1	March 31, 2031	no	no	no	no
Pyrethrin	1.5567209	17	11	0.09	1.55	7	August 31, 2023	no	yes	no	no
Pyrimethanil	1	1	1	1.00	1.00	1	April 30, 2023	no	no	no	no
Pyriofenone	0.09	1	1	0.09	1.00	1	January 31, 2025	no	no	no	no

(*continued on next page*)

(*continued*)

Active substances	kg/ha	Application number	Number of fields	kg a.s/ha/ application	If applied, how often	Number of products	A.s. Registration EU	Candidate for substitution (draft list 2015 EU)	Use in organic	Bio control agents (microO)	Semiochemicals
Quinmerac	0.875	2	2	0.44	1.00	1	July 31, 2024	no	no	no	no
Quizalofop-P-ethyl	0.1	1	1	0.10	1.00	1	November 30, 2023	yes	no	no	no
Saccharomyces cerevisiae LAS117	0	1	1	0.00	1.00	1	July 06, 2031	no	yes	yes	no
S-Metolachlor	4.875	4	4	1.22	1.00	1	July 31, 2023	no	no	no	no
Sodium hydrogen carbonate	6.6825	4	1	1.67	4.00	1	undetermined	no	no	no	no
Spinetorame	0.125	2	2	0.06	1.00	1	45473	no	no	no	no
Spinosad	0.7458	9	7	0.08	1.29	4	April 30, 2023	no	yes	no	no
Spirotetramat	1.922	15	8	0.13	1.88	3	April 30, 2024	no	no	no	no
Spiroxamine	0.3	1	1	0.30	1.00	1	December 31, 2023	no	no	no	no
Steinernema carpocapsae	1	1	1	1.00	1.00	1		no	yes	yes	no
Sulfoxaflor	0.132	6	3	0.02	2.00	2	45887	no	no	no	no
Sulfur	537.0127	194	29	2.77	6.69	16		no	yes	no	no
Sulfur hydroxyde	79.856	51	7	1.57	7.29	1		no	yes	no	no
Tau-fluvalinate	0.12	2	2	0.06	1.00	2	45535	no	no	no	no
Tebuconazole	1.57795	14	10	0.11	1.40	8	August 31, 2023	yes	no	no	no
Tembotrione	0.176	4	2	0.04	2.00	1	July 31, 2024	no	no	no	no
Terbuthylazine	1.625	4	4	0.41	1.00	1	December 31, 2024	no	no	no	no
Terpen alcohol	2.14795	20	5	0.11	4.00	2		no	no	no	no
Tetraconazole	0.0768	3	2	0.03	1.50	2	45291	no	no	no	no
Thiacloprid	0.1536	1	1	0.15	1.00	1	February 03, 2020	yes	no	no	no
Thiamethoxam	0	1	1	0.00	1.00	1	April 30, 2019	no	no	no	no
Thiencarbazone-methyl	0.2257	8	8	0.03	1.00	2	September 30, 2024	no	no	no	no
Thiophanate-methyl	4.075	5	2	0.82	2.50	2	October 19, 2020	no	no	no	no
Thymol	0.024	1	1	0.02	1.00	1	November 30, 2023	no	yes	no	no
Tribenuron-methyl	0.10525	4	3	0.03	1.33	3	January 30, 2034	no	no	no	no
Trichoderma asperellum strain T34, colony-forming units 1x109	0.036	3	1	0.01	3.00	1	May 31, 2023	no	yes	yes	no
Trichoderma atroviride	0	1	1	0.00	1.00	1	April 30, 2023	no	yes	yes	no
Trifloxystrobin	2.125	18	10	0.12	1.80	4	July 31, 2033	no	no	no	no
Urtica dioica	0	5	1	0.00	5.00	1		no	yes	no	no
Urtica urens	0	5	1	0.00	5.00	1		no	yes	no	no
Zoxamide	1.8668	9	6	0.21	1.50	4	48760	no	no	no	no
Alcohol ethoxylate	0.4075	10	2	0.04	5.00	1					

Appendix 4. Overview of products with missing application recommendations per case study site (CSS)

Case Study Site	Number of products with missing recommendation	Number of applications with missing recommendation	Type of products
CSS1	12	26	2 adjuvants, 2 fertilizers, 3 fungicides, 1 herbicide, 1 insecticide, 1 pH regulator, 1 soil amendment, 1 unknown product
CSS2	15	34	1 adjuvant, 11 fungicides, 2 insecticides, 1 pH regulator
CSS3	16	63	2 adjuvants, 4 fertilizers, 1 foliar fertilizer, 1 insecticide, 2 plant defense stimulators, 4 unknown products, 2 wetting agents
CSS4	1	1	1 insecticides
CSS5	7	52	2 fungicides, 1 herbicides, 4 insecticides
CSS6	4	17	1 fungicide, 3 insecticides
CSS7	1	2	1 herbicide
CSS8	10	15	2 fertilizers, 3 fungicides, 2 herbicides, 2 insecticides, 1 seed treatment product
CSS9	6	22	1 chelator, 1 fertilizer, 2 fungicides, 1 herbicide, 1 pH regulator
CSS10	6	6	2 fungicides, 3 herbicides, 1 growth regulator,
CSS11	10	20	1 adjuvant, 5 herbicides, 1 insecticide, 3 seed treatment products

Appendix 5. PPP application patterns across farming systems and crops

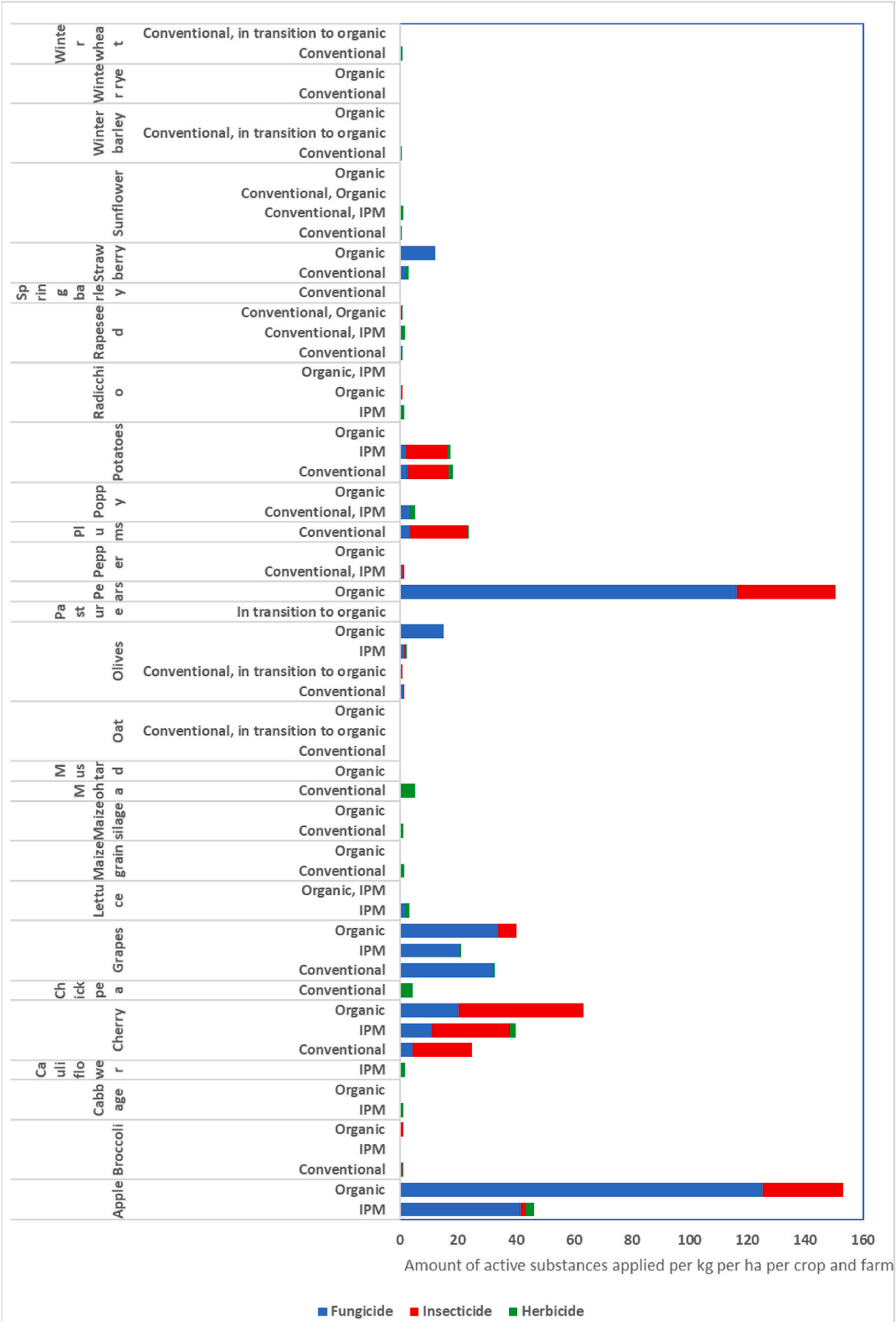

Fig. 1. Overview of cumulative amounts of fungicides, insecticides and herbicides applied per crop in kg/ha per farming practice.

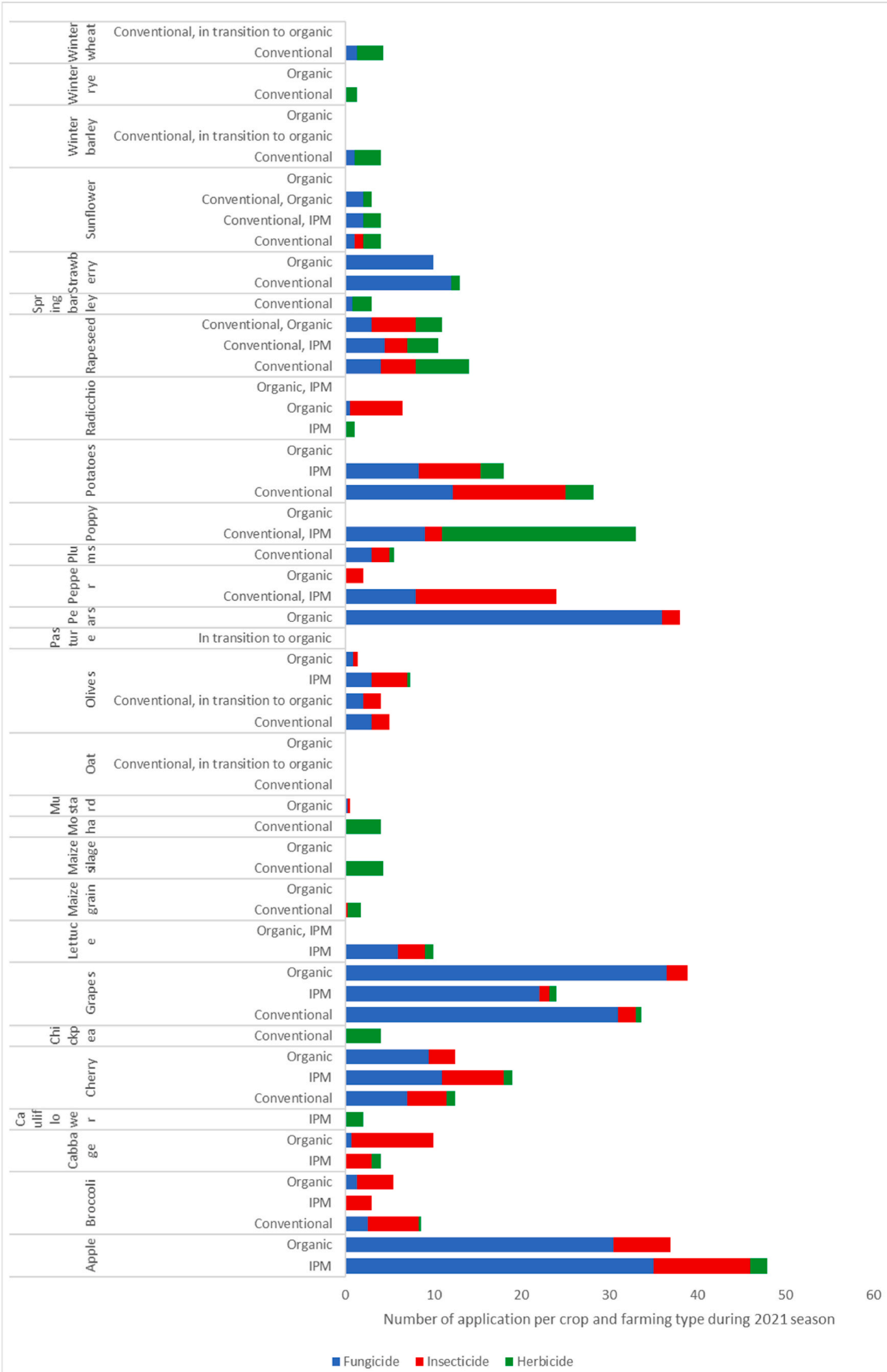

Fig. 2. cumulative application of fungicides, insecticides, herbicides at field level in different farming practices.

Appendix 6. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.143577.

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