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Typology for Decision Support Systems in Integrated Pest Management and Its Implementation as a Web Application

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Abstract: Decision support systems (DSSs) enable the optimisation of pesticide application timing to increase pesticide efficacy and thus reduce pesticide use without compromising yield quality and quantity. Limited access to information about available DSSs for use in integrated pest management (IPM) is a major barrier to the uptake of DSSs for IPM across Europe. To overcome this barrier, a typology for DSSs for IPM in Europe was developed, introducing a systematic approach to describe the ever-growing number of DSSs for IPM. The developed IPM-DSS typology was implemented in the free web tool "IPM Adviser", where currently 79 IPM DSSs are described with over 50 attributes describing their structural and performance characteristics. The information about IPM DSSs, which was previously scattered on different websites and difficult to compare, is now standardised and presented in a uniform way, so that it is possible to compare different IPM DSSs on the basis of all the attributes described. The presented IPM-DSS typology implemented in the web tool IPM Adviser facilitates the dissemination and uptake of DSSs for IPM and thus contributes to the achievement of the EU targets for the sustainable use of pesticides.

Keywords: decision support system; integrated pest management; DSS uptake; typology; web tool; user experience; sustainable use of pesticides

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1. Introduction

Since 2009, the Sustainable Use of Pesticides Directive (SUD) [1] has mandated the minimisation and sustainable use of pesticides in agriculture across the European Union (EU). The European Commission has since assessed the implementation of this Directive in the EU and published shortcomings in its implementation in two reports published in 2017 [2] and 2020 [3]. The main shortcomings identified were a lack of education and knowledge transfer, insufficient use of alternative methods for crop protection and a lack of holistic approaches to implementing sustainable practices in the use of pesticides, which led to the proposal for a regulation [4] to replace the above-mentioned Directive on the sustainable use of pesticides. The pursuit of the EU objectives of reduced and more sustainable use of pesticides outlined in the Directives [1,4] is also supported by strategies under the European Green Deal [5], the Farm to Fork Strategy [6], and the Biodiversity Strategy [7]. In 2022, the European Commission set targets to reduce of the environmental risk of chemical pesticides by 50% by 2030 compared to a three-year average (i.e., 2011–2013), reduce pesticide use by 50% compared to a three-year average (i.e., 2015–2017), and take a measures to conserve biodiversity through legislative proposals [4]. Although the proposed Sustainable Use of Pesticides Regulation was rejected in its proposed state by the Parliament in late 2023 [8], the SUD remains in place, along with existing targets. The targets for the reduction of pesticide use are to be achieved through various approaches, such as the implementation of appropriate crop rotation, the use of non-chemical pest control methods, the orientation of agricultural production towards organic or integrated farming, and the protection of agriculture [5,9]. In addition to the above strategies, the Strategy on Shaping Europe's Digital Future [10] aims to address the challenge of the EU's green and digital transformation, including the digitisation of agriculture, which fits into the context of the European Green Deal. Despite the EU's encouragement, Tataridas et al. [11] point out that the target of reducing environmental risk and pesticide use by 50% by 2030 is very ambitious, while Beckman et al. [12] also point out the potential local and global negative economic impacts of achieving this target.

Integrated pest management (IPM) is a sustainable strategy for managing pests though a combination of practices that prevent and/or minimise the impact of diseases, weeds, or invertebrate pests on crops [13]. IPM strategies should be holistic and include the judicious use of synthetic chemical pesticides where all other approaches have been exhausted. Organic farming may also follow IPM strategies, though the range of pesticides permitted under organic production is greatly restricted. IPM therefore provides an effective framework to support all farmers in their transition towards reduced pesticide inputs while maintaining the productivity and profitability of their cropping systems. IPM strategies are, however, more demanding on the knowledge and experience of farmers and their advisors, and they increase the complexity of decision-making on both the need to apply pesticides and the details of subsequent applications (e.g., time of spraying) to achieve satisfactory efficacy while reducing the amount of pesticides used. Decision support systems (DSSs) are designed to help farmers and farm advisors in these complex decision-making processes.

DSSs are interactive, computer-based systems that assist decision makers in one or more decision-making processes and guide them to optimal solutions/next steps [14]. They improve the accuracy and efficacy of IPM decision-making [15–24] by using integrated decision rules, algorithms, and models in conjunction with one or more databases and user input data (e.g., crop or pest observations) [25,26]. Innovations in information technology (IT) and associated digital infrastructure are driving the rapid development of IPM DSSs [27], and evidence for the benefits of DSSs is well established [15–22,28]. The proportion of farmers and farm advisors reporting regular consultation of IPM DSSs in Europe is, however, relatively low [29–31]. This is in part due to specific crop monitoring requirements that many DSSs require in order to run, which farmers may be unwilling or unable to provide [32]. Another obstacle is the availability of DSSs, which are often developed in isolation in different parts of Europe and may each be tied to a subscription fee [31].

The European project IPM Decisions (grant number 817617, https://www.ipmdecisions.net/, accessed on 10 November 2023) aimed to improve access to and the uptake of DSSs across Europe. As part of this, a single platform was created (http://www.platform.ipmdecisions.net/, accessed on 10 November 2023), into which DSSs can be integrated and made accessible for users to consult.

Summary reviews of DSSs for application in agriculture are often provided as simple lists of available DSSs, without systematic descriptions of their technical characteristics and user properties. A review of IT in agriculture [33], which includes also DSSs, provides brief descriptions of the decision problem addressed by DSSs. The reviews of DSSs for IPM available in India [34] and in the Midwestern US [35] provide general descriptions of DSSs as well as a comparison between them in terms of their applicability. Pertot et al. [36] describe the state of the art of DSSs for IPM in viticulture. In Appendix A, Rossi and colleagues [27] list the number of DSSs developed for a particular decision problem. Taechatanasat and Armstrong [37] reviewed DSSs in terms of data requirements. Extensive reviews of IPM DSSs were made by Damos [20] and Tonle et al. [38], each describing more than 20 DSSs, but the set of DSS features described in both reviews is rather limited due to the different aims of the reviews. The EuroBlight website [39] contains a similar brief description of some DSSs available in Europe for the control of late blight (*Phytophthora infestans*) and early blight (*Alternaria solani*) in potatoes. Despite very detailed reviews of DSSs, information about the functional and structural characteristics of DSSs (e.g., in which country the DSS is validated, how the DSS obtains weather data, whether it is freely accessible, what kind of results it provides) is missing or provided in a too-general way. In addition, the reviews usually follow their own criteria for DSS descriptions which are specifically adapted to the purpose of their study. This makes comparisons between the DSSs described by different authors difficult or even impossible. The development of a typology to describe the characteristics of DSSs developed for IPM in Europe would solve these problems. The typology would introduce a consistent and uniform approach to describing and comparing IPM DSSs and help users obtain the information they need to select the most appropriate IPM DSS for their needs. A systematically structured, transparent, and understandable description of DSS will bring users closer to the benefits of DSS and consequently facilitate the achievement of the objectives for the sustainable use of pesticides in Europe.

This article aims to achieve the following: (1) develop a typology for a consistent and uniform description and comparison of DSSs for application in IPM in Europe; (2) Introduce a web-based tool, "IPM adviser", based on the implementation of the developed typology; and (3) publish descriptions of 79 available DSSs for IPM applied in Europe to present the user's features of the "IPM adviser" web tool.

2. Materials and Methods

Typology is a method of classification in which, based on a hierarchical structure of related categories (dimensions) of the object, concept, organism, or domain being described (cases), cases are classified into groups (types) on the basis of their similarities and differences [40,41], where dimensions represent concepts and not necessarily empirical examples [40,42]. They are of utmost importance in discovering and explaining the great diversity and dispersion of information in the field they classify. To the best of the authors' knowledge, there is currently no typology that systematises and provides information on DSS for IPM, although there is a considerable need for it.

The development of typologies is a well-established practice to systematically link otherwise dispersed information. However, there is relatively little guidance in the literature on how to create them [43].

2.1. Development of the DSS Typology for IPM in Europe

Our aim in developing a typology was to assess the suitability of different IPM DSSs for the specific needs of end users. To overcome the lack of literature describing a methodology for creating typologies [43], our experiences in developing decision models [44–51] and agricultural DSSs (Soil Navigator (http://www.soilnavigator.eu/, accessed on 1 December 2023), Pathfinder (https://pathfinder.ijs.si/, accessed on 1 December 2023), Resource Amplifier (https://resourceamplifier.ijs.si/, accessed on 1 December 2023), and SPON (https://spon.si/, accessed on 1 December 2023)) were used to introduce the methodology for the development of a qualitative multi-criteria typology.

Each dimension of the IPM DSS typology was developed by integrating bottom-up and top-down approaches (Figure 1). The former is based on the available information on DSSs, and the latter is based on a decomposition of overarching dimensions into intermediate aggregate criteria that integrate the descriptive criteria from the bottom-up approach [52].

(i) Top-down approach

In the top-down approach to IPM-DSS typology development, the purpose, objectives, and end users of DSSs were considered, as well as the spatial and temporal constraints on their use. To avoid biases in the structure of the typology (e.g., individual preferences and characteristics from IPM DSS developers favouring their DSS), this step was based on our own experience and the extensive review of available literature on the development of agroecological DSSs [14,17,19,25,27,29,30,38,48,50,53–57]. In addition, the literature review also indirectly represented the users of IPM DSSs, as the characteristics and features that users want and need are described [19,27,29,30,58,59]. This information was then used to identify overarching thematic dimensions. For each dimension, an individual typology was developed by subdividing each of the five overarching dimensions into contextually related attributes towards the lower levels. The result of this work is a hierarchically linked structure of attributes that were used in the next step as a theoretical framework for the further development of the typology. Although the typology was structured as five independent dimensions of the typology, all five overarching dimensions were created simultaneously and with the same approach, forming a single IPM-DSS typology.

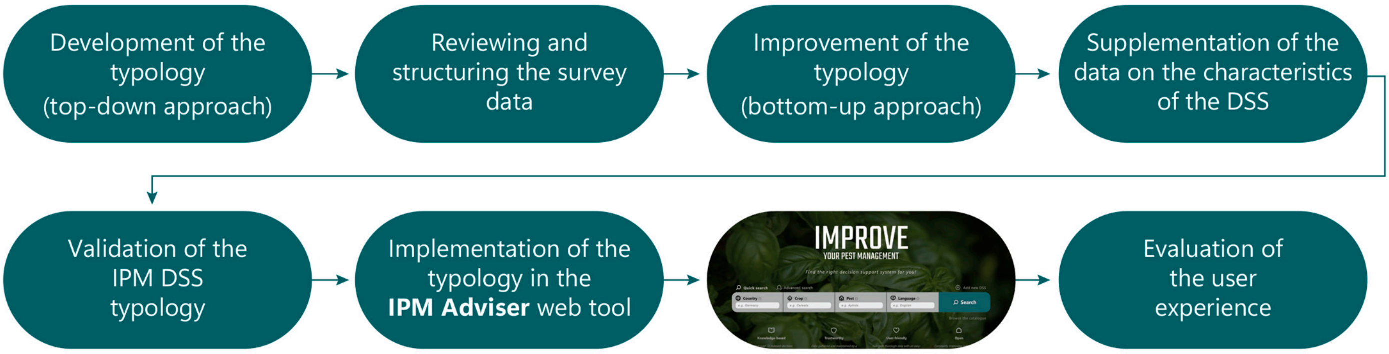


Figure 1. Schematic representation of the process of developing and implementing the typology for IPM DSSs in Europe.

(ii) Initial data collection

Before proceeding with the bottom-up approach to IPM-DSS typology development, data on developed and implemented IPM DSSs had to be collected. This process was carried out in two steps and started with a survey of IPM Decisions project partners from 12 European countries in 2019 (Table 1). The survey focused on DSSs that help manage diseases, pests, or weeds in crops relevant to European farmers. It addressed the following aspects: basic information about DSSs, such as name, owner, and web page; the language of the user interface, information about the price, the estimated number of users, the type of decision, target crops/pests, the type of output, the typical user, required input data, required weather data, and additional information about weather data such as spatial context and units; and whether the underlying models are documented. Most of the questions had an option to write in elaborations and comments. As the aim of this study was not to validate or compare the DSS outputs (results/predictions) based on the precision and accuracy of the DSS results, but to provide structural and technical information, information on the accuracy and precision of the IPM DSS results were not collected and considered.

Table 1. Regions of DSSs' geographic focus with corresponding countries and the number of DSSs currently included in the typology.

Region	Country	No. of Currently Included DSS
Northern Europe	Denmark ■, Estonia, Finland ■, Latvia, Lithuania ■, Norway ■, Sweden ■.	37
Central Europe	Austria, Belgium, Czech Republic, Germany ■, Hungary, Ireland, Luxembourg, Netherlands ■, Poland, Romania, Slovakia, Slovenia ■, Switzerland, United Kingdom ■.	35
Southern Europe	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, France ■, Greece ■, Italy ■, Kosovo, Malta, Montenegro, North Macedonia, Portugal, Serbia, Spain.	7

■ Countries participating in EU project IPM Decisions.

The survey resulted in 73 responses collected. After the initial survey, seven additional DSSs were described, resulting in a catalogue with 79 described DSSs for IPM in Europe. Some of the respondents provided us with temporary test usernames and passwords for five DSSs (6%). If some information on the characteristics of the DSS was not provided (e.g., only the name of the DSS was provided), the missing information was obtained from the publications, websites, or the web based-application of the DSS, without subscription to the DSS. All IPM DSSs identified through the survey were described and no further selection for inclusion in the catalogue was made on the basis of criteria such as accuracy and/or the availability of validation data. The obtained qualitative structural and functional characteristics of the DSSs were stored in the catalogue of identified existing DSSs for IPM in Europe, which served as an initial qualitative database [60].

(iii) Bottom-up approach

Once the theoretical framework of the typology is structured and the initial data on IPM DSS were obtained, the typology structure was reviewed and improved based on the data obtained from the survey. In this step, the data were analysed to identify the scale of qualitative values and group similar data to form categories that represent the concepts found in the data. The relevance of the data to the bottom-level attributes was reviewed, and minor changes were implemented to the wording and structure where necessary. In addition, the data collected during initial data collection were translated into qualitative values, which are used in the typology (Appendix A). Finally, additional specific data requirements were identified.

(iv) Supplementation of the data and integration of both approaches

The second round of data collection followed, after the top-down and bottom-up approaches were completed. The catalogue of existing DSSs for IPM in Europe [60] was supplemented with some of the qualitative structural and functional characteristics of DSSs needed to populate the developed typology [61]. The data were supplemented by checking the websites of DSS providers or developers, and additional information about DSS was obtained through interpretation of a combination of the characteristics already described, clearly labelling or separating interpretations or assumptions from other, more reliable information about DSS. In this way, a high degree of data transparency was obtained. In the typology, only five attributes out of more than 50 allow for assumed values. These are "Country of development", geographic focus ("Northern Europe", "Central Europe", "Southern Europe"), and spatial constraint ("Space") (Appendix A). All assumed values have pre-defined rules based on which assumptions were made. In addition, all assumed values are clearly marked also in the IPM Adviser web tool. All the data used to complete the catalogue of DSSs described above was obtained without having to create an account or pay for a subscription to any DSS.

Once the typology was developed, it was tested by comparing it to the original data and obtaining feedback from domain experts (i.e., users and developers of DSSs). The typology can be revised or refined based on these assessments. Once the typology is validated, it serves as a framework for analysing and interpreting the qualitative characteristics of DSSs for IPM. In addition, the qualitative typology provides a structured way to explore relationships, connections, and variations within the assessed DSSs, facilitates their further analysis, and helps to understand their complex phenomena (i.e., similarities and differences between assessed IPM DSSs).

2.2. Implementation of the Developed IPM-DSS Typology into the Web Tool "IPM Adviser"

The first version of the of the IPM-DSS typology was Excel-based and so had limited public application. The typology was then developed as a web application with a dedicated interactive graphical user interface (GUI) called "IPM Adviser". IPM Adviser provides information on the functional and structural characteristics of the DSSs, enables their comparison, and highlights both differences and similarities of the DSSs described with the typology. The aim of this was to facilitate its usability and expand the pool of potential users.

2.2.1. Development of the IPM Adviser Web Tool

The development of IPM Adviser followed the standard full-stack process for creating a web application, which includes the development of the client-side GUI (frontend) and server-side (backend) parts of an application [62]. The frontend is a single-page application that offers a user-friendly interface for searching for and/or browsing IPM DSSs using typology criteria. Angular [63] was chosen as the frontend framework due to its robustness, scalability, and ability to create reusable components. The backend is responsible for handling data management, processing search queries, and serving responses to the frontend. NodeJS [64] was chosen as the backend technology due to its ability to handle a large number of concurrent requests and support for asynchronous programming. Sequelize [65] is used for object relational mapping (ORM) as an interface between the NodeJS backend and the PostgreSQL [66] database where the data are organised according to the presented typology. The frontend and backend communicate via a REST interface, allowing for a seamless integration of the application and eventual connectivity with other platforms or DSSs. A secure connection is established between the backend and frontend with a self-signed SSL certificate. Search statistics are collected anonymously.

IPM Adviser also communicates with the related IPM Decisions platform [67], where users can obtain results of the included DSSs for IPM but do not have access to their structural or functional characteristics. The exchange of information between IPM Adviser and the IPM Decisions platform takes place in both directions via an API. IPM Adviser can send statistics about the most frequently searched and examined DSSs in the typology to the IPM Decisions platform. This information enables platform operators to identify users' DSS preferences and helps them select the most prioritised DSSs for inclusion in the platform (if they are not included yet). On the other hand, IPM Adviser receives additional information about the included DSSs (e.g., detailed descriptions, logo, and other relevant information) from the IPM Decisions platform.

2.2.2. Graphical Design of the User Interface

First, the objectives of the web tool were analysed, focusing on effective visual communication and a positive user experience. The target user groups were defined: farmers, farm advisors, researchers, and DSS developers.

In the second phase, various similar web-based solutions from other domains focusing on transport providers, booking services, online shops, and educational platforms were evaluated. We analysed how their features affect the user experience, looking in particular at search methods, result displays, option analysis, and additional features. These solutions were compared with our own design, identifying similarities, differences, and areas for improvement.

The development concept for the tool was to focus on simplicity and efficiency of use. The search process was streamlined by placing the input fields and the search button in one line and simplifying the field names and symbols. For displaying results, a structured and predictable layout was selected, showing essential information first and allowing users to access additional details in subsequent steps. In addition, the layout of filters was carefully designed to allow for the intuitive selection and deselection of categories, with increased contrast for active filters and options to open specific categories or clear all filters with a single click.

In the last stage, the visual aspects of the GUI were unified to create a predictable and user-friendly experience. A clear visual hierarchy of information was implemented, enhancing the contrast between the different levels of importance associated with different DSS metrics. A systematic display of graphical elements was implemented to distinguish between clickable elements in colour and static elements in greyscale, and it was enhanced using visually consistent icons to represent key concepts.

2.2.3. Functions of the IPM Adviser Web Tool

The tool contains four sets of functions: (1) search, in which the user selects the desired DSS characteristics by entering or selecting qualitative descriptive criteria; (2) results, where the DSSs that match the user's selection criteria are displayed, along with both brief and detailed descriptions of the DSS that match the selection criteria; (3) analysis, where the user compares up to four DSSs at a time and the system highlights similarities or differences between the DSSs during the comparison; (4) other functions such as marking the inclusion of DSSs in the IPM decision platform [67], reporting updates, adding new DSSs, and browsing the entire catalogue of included DSSs for IPM in Europe.

2.3. Validation

(i) Validation of the typology

Validation of the developed IPM DSS typology was performed by checking if the descriptive attributes to populate the typology can be obtained without creating an account or paying a DSS subscription. To validate the suitability of the descriptive attributes included in the developed IPM DSS typology, data collected in the catalogue [60], supplemented by some of the qualitative structural and functional characteristics of the DSSs [61], were used to describe 79 DSSs for IPM in Europe.

(ii) Evaluation of the IPM Adviser web tool user experience

The user experience of the IPM Adviser web tool was evaluated using the widely accepted System Usability Scale (SUS) method [68], which provides a reliable usability score even for smaller-sized samples (e.g., 12–14 samples) [69]. In November 2023, two demonstration lectures were conducted at two universities in Slovenia (University of Maribor, Faculty of Agriculture and Life Sciences, and University of Ljubljana, Biotechnical Faculty, Department of Agronomy) for agronomy students and staff. These represent the future workers in the agronomy sector as farmers, farm advisors, or teachers of future generations of agronomists and, therefore, a very important target group of the IPM Adviser. The demonstration lectures were held in person and the participants were asked to bring their own computer. After the presentation lecture on the tool, the participants had time to explore the functionalities of the IPM Adviser web tool by themselves. After they were familiar with the tool, the participants were presented with the validated Slovene translation [70] of the SUS questionnaire in an online format.

3. Results

3.1. Typology for IPM DSSs in Europe

The typology of DSSs for IPM in Europe consists of five overarching dimensions: (1) basic information, which describes basic information about the DSS; (2) challenge, which describes the scope and constraints of the DSS; (3) decision problem, which describes the decision problem; (4) implementation, which describes the decision analysis and data input requirements for the operation of the DSS; and (5) application, which describes the end users for whom the DSS is intended and the format of the DSS results (Figure 2).

3.1.1. Basic Information

The first dimension of the developed typology, "Basic information", provides information needed for the identification of and access to the DSS. This includes information about the name of the DSS, a link to the DSS or to the website of the DSS provider, information about the owner of the DSS, the country in which it was developed, and the country in which the DSS was validated. Based on the latter two pieces of information, the category "Geographic focus" was introduced, which defines the regions which correspond to the climatic categorisation of the environment of Europe where a particular DSS could be used with little or no needed adaptations: (1) Atlantic—Northern Europe, (2) Continental—Central Europe, and (3) Mediterranean—Southern Europe [71] (Table 1).

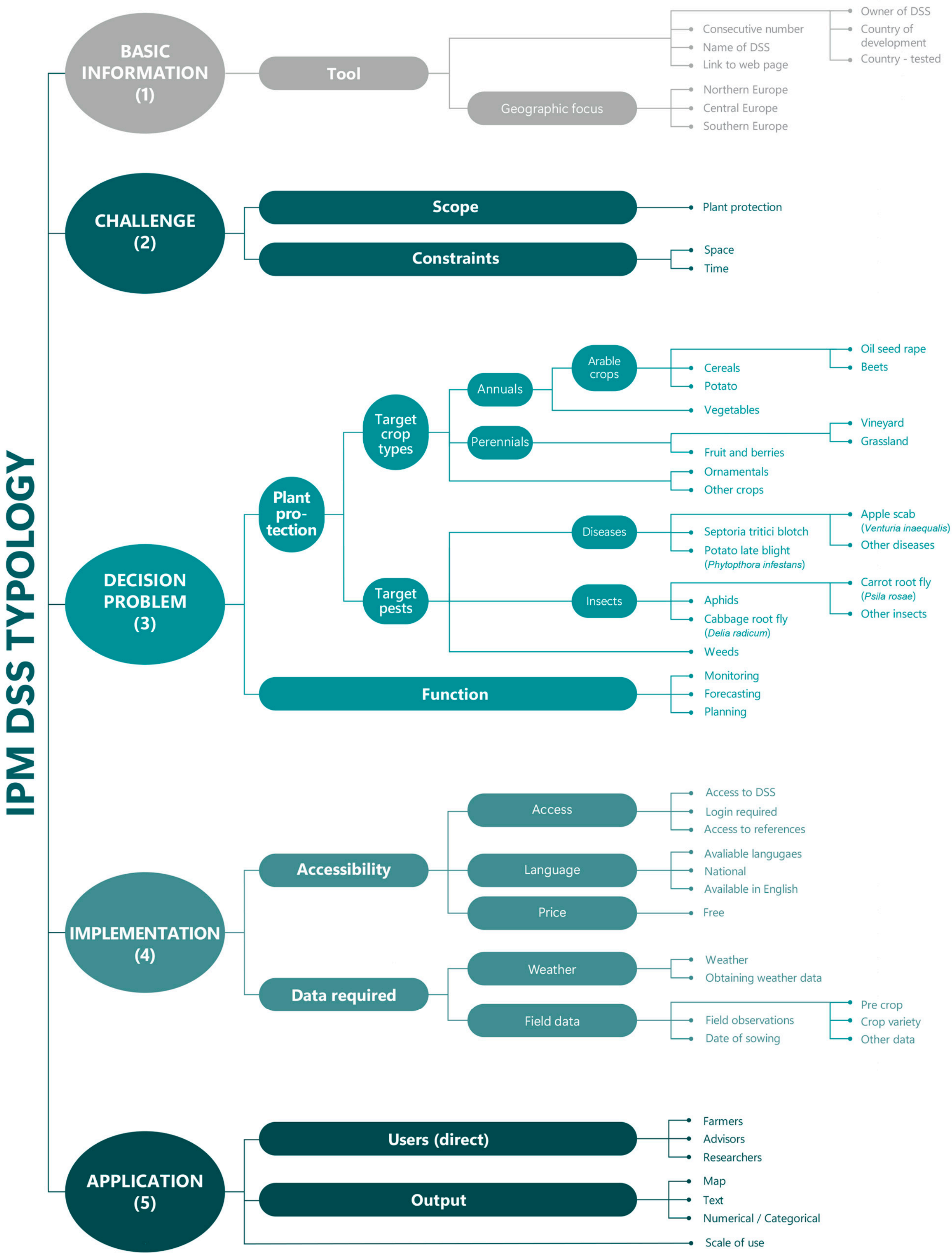


Figure 2. Schematic representation of the developed DSS typology for IPM showing the hierarchical levels for all five dimensions of the typology: (1) basic information, (2) challenge, (3) decision problem, (4) implementation, and (5) application.

3.1.2. Challenge

The “Challenge” dimension of the developed IPM DSS typology is described by criteria providing information on the scope of a particular DSS, as well as spatial and temporal constraints of its application. The typology currently includes only DSSs focused on “plant protection” challenges because it was developed in the framework of the IPM Decisions project. However, as new DSSs are added, the typology plans to include other definitions of agri-environmental problems such as water pollution, soil erosion, irrigation, and biodiversity loss. The criterium “Constraints”, which is in the context of ecological modelling defined as limitations imposed on the model or DSS to ensure its accuracy and relevance, is further divided into descriptive sub-criteria “Space”—with the values “national” or “international”—and “Time”—with the values “short-term”, “long-term”, and “both”.

3.1.3. Decision Problem

The dimension “Decision problem” is described by criteria that provide information about the decision problem that is solved by the DSS and consists of the criteria “Plant protection” and “Function”. The “Plant protection” criterium is further subdivided into criteria describing the target organisms of the DSS (i.e., “Target crop types” and “Target pests”).

The criterium “Target crop types” is divided into “Annuals” and “Perennials”. As the subgroup “Ornamentals” is very diverse and can include both annual and perennial plants, it is listed separately in the typology. The criterium “Annuals” is subdivided into “Arable crops” and “Vegetables”, whereby “Arable crops” is further subdivided into crops that are frequently covered by the DSS (cereals, potatoes, oilseed rape, and beets). The criterium “Perennials” is subdivided into fruit and berries, vineyard, and grassland.

The criterium “Target pests” is subdivided to “Diseases”, “Insects”, and “Weeds”, whereas “Diseases” is subdivided into diseases frequently covered by DSSs (i.e., septoria tritici blotch (*Septotia tritici*), potato late blight (*Phytopthora infestans*), apple scab (*Venturia inaequalis*)) and “Other diseases”. The criterium “Insects” is subdivided into pests frequently covered by DSSs (i.e., aphids, cabbage root fly (*Delia radicum*), carrot root fly (*Psila rosae*)) and “Other insects”.

The criterium “Function” describes three main types of DSS functions and consists of “Monitoring” (i.e., monitoring the abundance of diseases, insects, and weeds), “Forecasting” (i.e., predicting disease occurrence and the abundance of insects and weeds), and “Planning” plant protection activities (e.g., specific treatment recommendations).

3.1.4. Implementation

The implementation of a DSS is a very important aspect of the DSS typology, since DSSs that are perfectly suited to the user’s needs in all the features described previously (Sections 3.1.1–3.1.3) cannot be used if the user does not have the infrastructure required to run the DSS or does not understand the language of the user interface. The “Implementation” dimension of the typology thus describes the technical aspects of the included DSSs and consists of the criteria “Accessibility” and “Data required”.

The criteria “Accessibility” is further divided into three subgroups: “Access”, “Language”, and “Price”. “Access” includes information about the type of access to the DSS (online/offline), login requirements, and the availability of peer-reviewed references about the DSS. The “Language” criterium describes the supported DSS interface languages and is divided into “Available languages”, which lists all languages supported by the DSS, “National” (i.e., available in the language of the country where the DSS was developed), and “Available in English” (yes/no). The last descriptive criterium is “price”, which has a subordinate descriptive criterium “Free” with the values “yes”, “no”, and “limited”. The latter means that a free version with restricted functions is available or that a limited group of people has free access (e.g., farmers from one country).

“Data required” is divided into “Weather” and “Field data” and informs the user about the type of data the DSS requires for operation. “Weather” is subdivided at a lower level into "Weather" and "Obtaining weather data". The former describes whether the DSS requires weather data for its operation, while the latter, with the values "no", "manual", and "automatic", describes how the DSS obtains weather data. The "Field data" criterium describes which types of field data the DSS requires for operation.

3.1.5. Application

In the last dimension of the typology, "Application", there are the descriptive criteria "Users (direct)", which defines who the primary target users of a particular DSS are (i.e., farmers, farm advisors or researchers); "Output", which describes the format in which the results of the DSS are displayed and is subdivided at the lowest level into "Map", "Text", and "Numerical/Categorical"; and the " Scale of use", which gives a rough estimate of the number of users of a particular DSS with the following values: small (0–1999), medium (2000–14,999), and large (>15,000). Although data on the area under each DSS would be much more informative than the number of users, it is unfortunately difficult to obtain or estimate this information, and it becomes even more complicated when trying to measure or estimate how many users are farm advisors and use DSS to advise on larger areas.

3.2. Validation of the IPM-DSS Typology

Validation was performed in four thematic dimensions of the developed typology (excluding the dimension (1) "Basic information"). The average fulfilment of all attributes in four thematic dimensions (n = 50) is 93% ± 7.2% (Table 2). The least fulfilled attribute in all four validated dimensions is "obtaining weather data" (dimension "Implementation") with 57.5% fulfilment. Since we had access data (temporary username and password) for only five included DSSs (6%), the validation results provide a rough estimate of the percentage of data in each dimension of the typology that can be obtained without a DSS subscription, demonstrating its usefulness in practice. Of the 79 DSSs described for IPM in Europe, most were developed in Northern Europe (47%), closely followed by Central Europe (44%) (Table 3). Most of the DSSs described were developed for disease management (57%) (Table 4). The vast majority of DSSs described with the typology are available in the national language of the country where the DSS was developed (97%). Of the DSSs described with the typology, 45 are available in English (57%). The 21 DSSs developed in UK (27%) are counted both as available in a national language and available in the English language.

Table 2. Average fulfilment of the attributes in the typology after the description of 79 IPM DSSs with the typology.

IPM DSS Typology Dimension	No. of Attributes Included in Each Dimension	Average Fulfilment
(2) Challenge	3	97% ± 2.9%
(3) Decision problem	25	93% ± 5.1%
(4) Implementation	15	93% ± 10.7%
(5) Application	7	94% ± 8.8%
Total	**50**	**93% ± 7.2%**

Table 3. Region and country of origin of DSSs described with typology and included in the IPM Adviser web tool.

Region of DSS Origin	Country of DSS Origin	No. of Considered DSSs
Northern Europe	Norway	20
	Denmark	10
	Finland	6
	Sweden	1

Table 3. *Cont.*

Region of DSS Origin	Country of DSS Origin	No. of Considered DSSs
Central Europe	United Kingdom	21
	Netherlands	11
	Germany	2
	Belgium	1
Southern Europe	France	7
Total	**9**	**79**

Table 4. Target application of the assessed DSSs.

Application of DSS	No. of Assessed DSSs *
Diseases	45
Insects	23
Weeds	6
n/a	5

* Some assessed DSSs provide decision support for more than one type of target (e.g., diseases and insects).

3.3. The Web Tool: IPM Adviser

The developed typology for IPM DSSs in Europe was implemented in the web tool IPM Adviser (https://ipmadviser.ijs.si/, accessed on 10 December 2023) to facilitate its accessibility and usefulness. The web tool allows users to easily view the functional and structural characteristics of described DSSs, compare them, and visit the developers' website or the IPM Decisions platform (if a DSS is available on the platform) to directly use the DSS that has the selected characteristics. The web tool IPM Adviser is available in English and addresses the problem of limited accessibility of information on DSSs that was identified in our previous research [31]. All functions and collected information are provided free of charge and can be accessed without creating an account. The IPM Adviser web tool has three main functions: (1) search, (2) results, and (3) analysis. In addition, the IPM Adviser web tool has several features that increase trust in the IPM Adviser tool and the data provided and improve the user experience.

(i) Search

The web tool offers different ways to search the DSSs: quick search and advanced search. The latter is divided into "Search by criteria" and "Search by name or ID".

In the quick search, the user enters the country of the DSS application, the pests, the crops, and the desired language of the DSS user interface (Figure 3). All fields are optional and will default to "any" if no criterium is selected.

In the advanced search, in the search mode "by criteria", the user selects the descriptive criteria that match his preferences in three steps (i.e., problem, analysis, and outcomes). In this search mode, all fields are optional and have the default setting "any". In the search mode "by name or ID", the user enters the trade name of the DSS or the tag ID with which the DSS is identified on the platform IPM Decisions.

(ii) Results

After selecting or entering descriptive criteria, the IPM Adviser web tool displays a list of DSSs that match the search criteria. The results in the IPM Adviser follow a clear structure of the typology. They are displayed in an easy-to-interpret format, which facilitates understanding and positive user experience. For all DSSs, basic descriptive information is provided first (Figure 4). Below each DSS, two to four buttons are displayed. Clicking on the "Details" button displays all the descriptive criteria of the selected DSS, divided into the content dimensions of the typology. Clicking on the "Comparison" button adds the DSS to the comparison. These two buttons are always displayed. Additionally, two other buttons can be displayed. Selecting "Website", either the website of the DSS or the website of the developer will open. For DSSs available on the IPM Decisions platform, the "Available on the IPM Decisions platform" button is displayed. Clicking on this button opens a short description of the IPM Decisions platform with a link and short DSS description in English, regardless of the language of the DSS user interface (this information is retrieved from the IPM Decisions platform via its API).

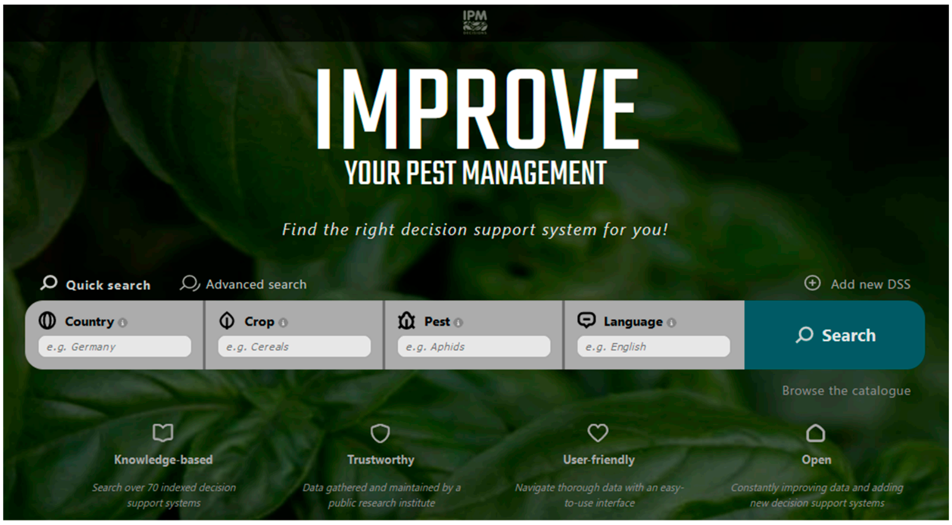


Figure 3. Landing page of IPM Adviser web tool with quick search (https://ipmadviser.ijs.si/, accessed on 10 December 2023).

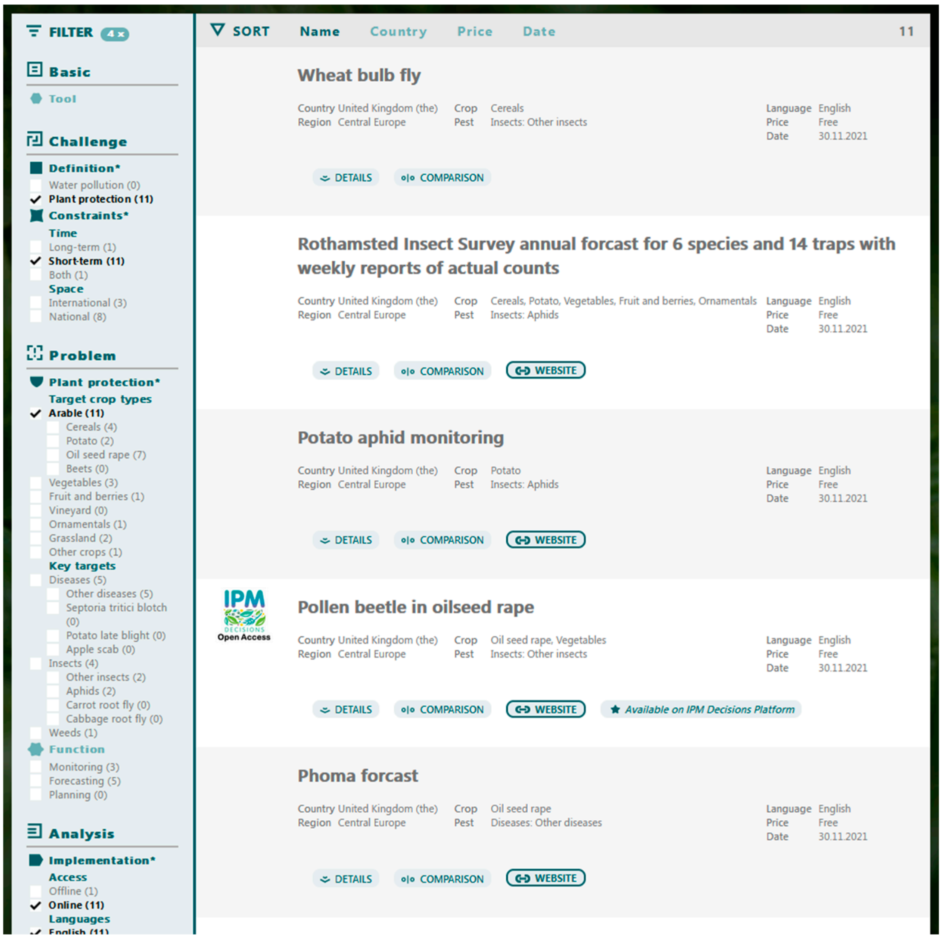
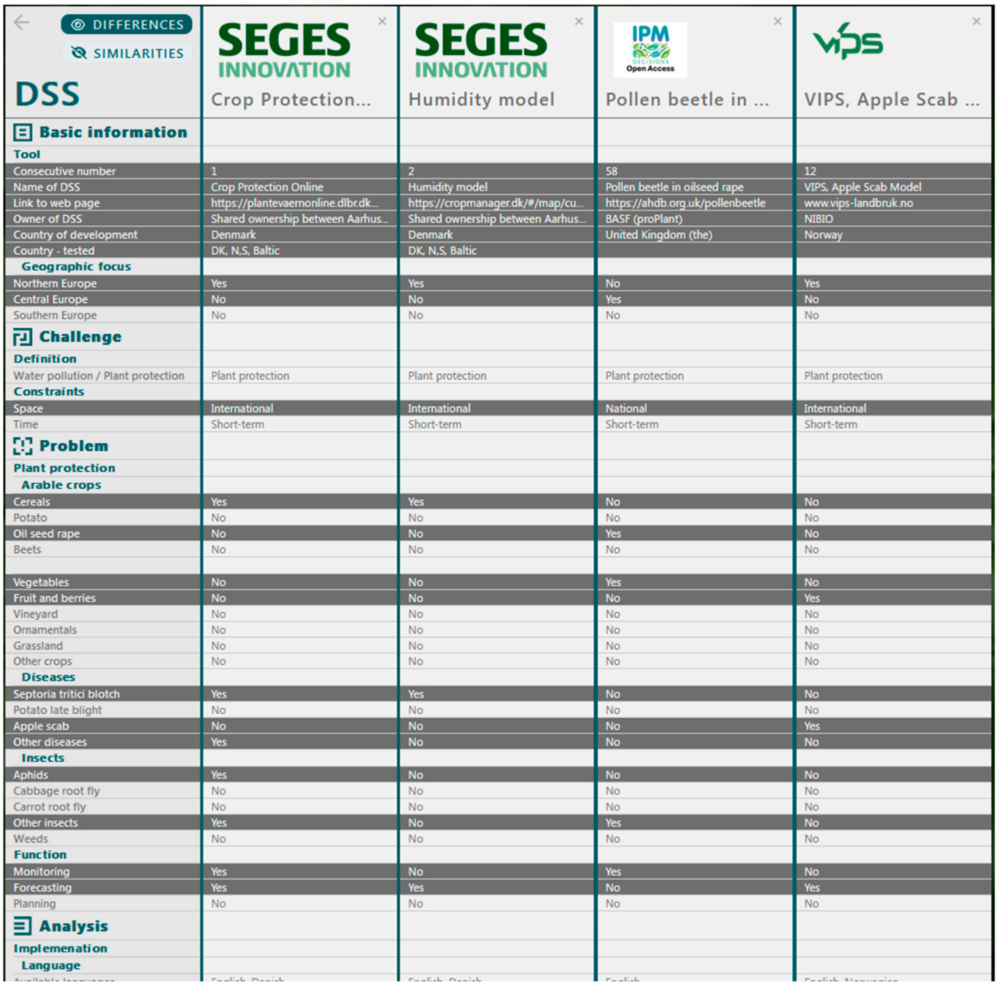


Figure 4. The default view of the IPM Adviser result page, which displays basic information about DSSs that meet selected typological criteria.

(iii) Analysis

In the next section of the IPM Adviser web tool, users can analyse the DSSs that match the selected typological criteria (results). On the results page (Figure 4), the selected descriptive criteria are displayed on the left-hand side, which the user can modify (add or remove). In all search modes (i.e., basic or advanced search), up to four DSS can be compared, and the user can tick whether all similarities or all differences between the compared DSSs should be marked (Figure 5).



DSS	Crop Protection...	Humidity model	Pollen beetle in ...	VIPS, Apple Scab ...
Basic information				
Tool				
Consecutive number	1	2	58	12
Name of DSS	Crop Protection Online	Humidity model	Pollen beetle in oilseed rape	VIPS, Apple Scab Model
Link to web page	https://plantevaernonline.dlbr.dk...	https://cropmanager.dk/#/map/cu...	https://ahdb.org.uk/pollenbeetle	www.vips-landbruk.no
Owner of DSS	Shared ownership between Aarhus...	Shared ownership between Aarhus...	BASF (proPlant)	NIBIO
Country of development	Denmark	Denmark	United Kingdom (the)	Norway
Country - tested	DK, N,S, Baltic	DK, N,S, Baltic		
Geographic focus				
Northern Europe	Yes	Yes	No	Yes
Central Europe	No	No	Yes	No
Southern Europe	No	No	No	No
Challenge				
Definition				
Water pollution / Plant protection	Plant protection	Plant protection	Plant protection	Plant protection
Constraints				
Space	International	International	National	International
Time	Short-term	Short-term	Short-term	Short-term
Problem				
Plant protection				
Arable crops				
Cereals	Yes	Yes	No	No
Potato	No	No	No	No
Oil seed rape	No	No	Yes	No
Beets	No	No	No	No
Vegetables	No	No	Yes	No
Fruit and berries	No	No	No	Yes
Vineyard	No	No	No	No
Ornamentals	No	No	No	No
Grassland	No	No	No	No
Other crops	No	No	No	No
Diseases				
Septoria tritici blotch	Yes	Yes	No	No
Potato late blight	No	No	No	No
Apple scab	No	No	No	Yes
Other diseases	Yes	No	No	No
Insects				
Aphids	Yes	No	No	No
Cabbage root fly	No	No	No	No
Carrot root fly	No	No	No	No
Other insects	Yes	No	Yes	No
Weeds	No	No	No	No
Function				
Monitoring	Yes	No	Yes	No
Forecasting	Yes	Yes	No	Yes
Planning	No	No	No	No
Analysis				
Implementation				
Language				

Figure 5. Comparison of selected DSSs with highlighted differences (dark grey). All description criteria are displayed in the structure that follows the structure of the developed typology.

(iv) Other

The IPM Adviser web tool enables and encourages users to add new DSSs using the "Add new DSS" button. Adding a new DSS is a two-step process. In the first step, the applicant submits a short contact form to the IPM Adviser web tool owners. In the second step, a meeting between the applicant and the IPM Adviser web tool owners is arranged, and all detailed information about the new DSS is inserted into the web tool.

One of the most important aspects of the IPM Adviser tool is the transparency of the typology structure and the independence of the DSS descriptions. As the typology was initially developed independently of the data (top-down approach, Section 2.1), its structure implemented in IPM Adviser is unbiased towards the individual DSS characteristics. DSS descriptions and their characteristics may change when the DSS is updated. IPM Adviser therefore allows updating the DSS descriptions. On the "Details" tab of each DSS, there is an "Update information" button that the user can use to alert the owners of IPM Adviser to available updated information about the DSS. Finally, users of IPM Adviser can also alert about updates via a contact form followed by an online meeting or an email exchange.

3.3.1. Typical Use of IPM Adviser Web Tool

The interface of the web tool IPM Adviser is designed to be easy to use and transparent for all target users (i.e., farmers, farm advisors, researchers, and DSS developers). The information provided can be used by different types of users for different purposes.

The purpose of the IPM Adviser tool is to facilitate the use of the IPM DSS typology by searching the list of IPM DSSs described for those that match the characteristics requested by users. After defining initial criteria, which are more general, at least for the quick search, detailed filters can be added to further narrow down the DSSs displayed. This process helps the user to find the DSS that best matches their desired characteristics. A typical use of the IPM Adviser web tool by farmers and farm advisors is to search for information on structural and performance characteristics of DSSs that meet their criteria or needs (i.e., their choice of descriptive criteria). First, the user selects the type of search (i.e., quick search or advanced search) and enters the desired criteria. After clicking the Search button, the IPM DSSs that match the entered criteria will be displayed together with their basic information (e.g., crop, pest, price, and language of interface). If there are several DSSs available that match the user's entered criteria, the user can review their detailed description or add additional filters (criteria). Alternatively, the user can add DSSs for comparison. Additional information for the most suitable DSS can also be obtained through the provided link to the website of the developers or owners. If the DSS is already included in the IPM Decisions platform, the user can read its description in English, regardless of the language of the DSS interface. The next step is either to register on the IPM Decisions platform, where the outputs from the selected DSSs are available for free (if the selected DSS is included in the platform) or to access the selected DSS through a provided link to its website.

When a user of IPM Adviser selects a specific IPM DSS, it is necessary for the DSS user to independently verify that its output is accurate and precise in practice for the specific conditions in which it will be used, as this information is not provided by the IPM Adviser tool. In addition, the user of the DSS must understand that the role of decision maker remains with them. The DSS is only a tool to help them through the complex decision-making process. The final decision as to whether or not the user follows the advice of the DSS is in the hands of the decision maker (e.g., farmer or farm advisor).

A typical use of the IPM Adviser tool by DSS developers and researchers is to check for shortcomings of the developed DSSs, such as in which region or for which combinations of crops and pests there is a shortage of developed DSSs. This information will become more important and relevant over time as even more DSSs are described with the typology.

3.3.2. Evaluation of the IPM Adviser User Experience

While the IPM Adviser web tool usability score is a measure of usability perceptions by a sample of users, it gave us an important insight into an important segment of the tool's target users as they are future farmers, farm advisors, and professors of future generations of farmers and farm advisors. The System Usability Scale evaluation is based on the results of 29 responses from potential users. The respondents' scores regarding the IPM Adviser web tool were in range from 42.5 to 92.5. The median is 72.5 and the standard deviation is 12.75. The average SUS score was 72.7, which is positioned in the range of the 65th to 69th percentile of scores of other sites and corresponds to a good user experience [72].

4. Discussion

Increasing pressure to reduce the use of pesticides and the growing complexity of IPM practices have highlighted the need for DSSs to help farmers and farm advisors make informed decisions about pest management strategies. However, the lack of a standardised approach to describing and comparing DSSs for IPM in Europe has made it difficult for users to find the tools best suited to their specific needs. This can hinder the adoption of these valuable tools and ultimately impede progress towards sustainable pest management practices.

The proposed typology for DSSs in IPM provides a bridge enabling users to access relevant knowledge in a structured and user-friendly way. By categorising IPM DSSs according to specific criteria such as target pests, crop types, and functions (i.e., monitoring, forecasting, planning), the typology enables users to efficiently find solutions tailored to their specific needs. This targeted approach to the DSS selection supports improved adoption, which can lead to reductions in pesticide use while maintaining yield quality and quantity [16,18–22,24]. This has a positive impact on the profitability of agricultural production [73,74], the alleviation of direct and indirect impacts on soil organisms [75], and the population of natural enemies in and around crops [74].

Several typologies have been developed to classify different areas of agriculture, such as typologies of farm structure, soils, and pesticides and typologies used to explain farmers' decisions to use certain agricultural practices, tools, etc. [52,76–84]. The IPM-DSS typology is an important addition to this wide range of typologies in the agricultural sector with an important impact on digitalisation in agriculture.

With its precisely structured dimensions illustrated by "Basic Information", "Challenge", and "Implementation", the IPM-DSS typology offers tangible benefits in the organisation and presentation of information. This structured approach improves accessibility and understanding for end users and enables farmers and farm advisors to navigate and select the most appropriate DSS based on their specific needs and taking into account limiting factors such as available infrastructure, required data, and language barriers.

The IPM-DSS typology described places a strong emphasis on technical considerations crucial for the usability of each DSS, particularly through the "Implementation" dimension. This prioritises emphasis on current and effective DSSs and lays the foundation for the rapid integration of intelligent and artificial intelligence-based tools. By taking technical aspects into account, the typology contributes to accelerating the digitalisation of agriculture by promoting state-of-the-art digital technologies for pest management. The structured framework acts also as a guide for the development of user-friendly interfaces for smart IPM tools, and it facilitates data integration between DSS and AI algorithms, enabling more sophisticated and personalised decision support. This paves the way for a future of informed agriculture empowered by both human expertise and data-driven insights.

The core principles of this typology harbour immense potential for adaptation, both within and beyond the realm of IPM. The structure can be readily adapted to include a IPM DSSs for a wider range of crops, pests, and associated decisions. Similar frameworks could also guide the development of typologies for DSS in conventional crop protection, organic farming, and regenerative agriculture. While each agricultural practice presents unique challenges and decision-making requirements, the underlying principles of structured information access and user-centredness of the IPM-DSS typology are adaptable to any new DSS typology in agronomy and agroecology.

The implementation of the IPM-DSS typology into the IPM Adviser web tool plays a key role in promoting the use of IPM DSSs. By providing easy access to DSSs for IPM, the tool enables users to filter DSSs by specific criteria such as country, pests, crops, and language to ensure that the selected DSS matches the unique characteristics of their farming environment. This targeted approach helps to introduce DSSs that are tailored to users' local specifics. For farmers and farm advisors, IPM Adviser is a valuable tool that makes it easier for them to find the DSS best suited to their needs. The tool allows them to compare different options and ensure that the chosen DSS meets their criteria and requirements. The transparent presentation of results and easy access to additional information via direct links contribute to a positive user experience. IPM Adviser provides DSS developers and researchers with a tool to assess the landscape of DSS development. It helps to identify regions with a lack of developed DSSs and enables the evaluation of existing solutions. This insight is invaluable for guiding research efforts and improving the overall quality of DSSs for crop protection. Encouraging user contributions to the platform, such as submitting new DSS information, promotes collaboration and ensures that the tool remains dynamic and relevant over time. To maintain transparency and ensure accurate descriptive data for each DSS, a two-step review process is performed when new DSSs are added or updates are proposed. This quality control process ensures the reliability of changes to the descriptions of existing DSSs or information on newly added DSSs.

The success of IPM depends on co-operation between researchers, farm advisors, and farmers, as well as support from wider supply chain actors and policy makers. The proposed typology serves as a common language that promotes knowledge exchange and breaks down communication barriers, especially through the "Application" dimension.

As agriculture increasingly adopts digital technologies, tools like IPM Adviser play a central role in connecting farmers and advisors with advanced DSSs [10]. Its user-friendly interface, robust search function, and analytical capabilities contribute to the digital transformation of crop protection practises. IPM Adviser is proof of how digital tools can improve accessibility, transparency, and sustainability in modern agriculture.

The developed typology and its implementation in the IPM Adviser web tool successfully contribute to the objective of the presented research, namely to overcome the identified main barriers to the adoption of DSSs in IPM in Europe, which are the lack of information about DSS and the lack of trust in DSS [31]. The IPM Adviser tool addresses these barriers by providing free access to information about DSSs, allowing users to compare different DSSs and facilitating the easy selection of DSSs that meet the needs of the users.

Despite their significant contributions, the IPM-DSS typology and the IPM Adviser tool face several challenges for further improvement of their effectiveness. Ongoing updates, integration with existing platforms and ontologies (e.g., EPPO), multilingual support, ensuring data quality, user engagement, the integration of new technologies, and collaboration with stakeholders are important areas for improvement. By addressing these challenges, the tools can play an even more important role in promoting sustainable IPM practices and reducing pesticide dependency in European agriculture.

5. Conclusions

The IPM-DSS typology represents a significant step forward in navigating the complex world of sustainable agriculture. It empowers users, encourages collaboration, and paves the way for the digitalisation of IPM practise.

The web tool IPM Adviser plays a key role in promoting the sustainable use of pesticides and helps farmers, farm advisors, and DSS developers to make informed decisions. Its importance for the digitalisation of agriculture is evident and demonstrates how technology can be used to address critical challenges in the field of crop protection. The positive rating on the System Usability Scale underlines its effectiveness and makes IPM Adviser a valuable tool for stakeholders in the agriculture and pest management domain.

The IPM Adviser tool currently contains descriptions of 79 IPM DSSs for Europe, which is a good start to show the usability of the IPM Adviser tool. Although it was not the aim of this research to describe all IPM DSSs, it is our endeavour to gradually include as many IPM DSSs descriptions as possible. This is possible due to the design of the web tool, which serves as a living document, allowing for its longevity. As the field of IPM DSS development is growing rapidly and it is difficult to keep track of every new DSS development across Europe due to language barriers and the lack of centralised points of contact for such information, we hope that users of the IPM Adviser tool will help to inform us of existing tools that are not currently described by the IPM DSS typology and that IPM DSS developers and users alike will adopt IPM Adviser as a central point of contact for such information as it has been developed for this purpose.

By collecting, structuring, and providing comprehensive information on various aspects of DSSs for use in IPM, we facilitate the adoption of DSSs among farmers and farm advisors across Europe. In addition, our results contribute to the implementation of the EU's Sustainable Use of Pesticides Directive [1]; they are aligned with the objectives of the

European Green Deal [5] and help to achieve the goals of the Farm to Fork Strategy [6] and the Biodiversity Strategy [7].

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Conflicts of Interest: Author Mark Ramsden was employed by the company RSK ADAS Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A. Schematic Representation of Version 1.0 of the Developed IPM-DSS Typology

V1.0 IPM-DSS TYPOLOGY

Dimension (top level)	Levels 2-5 represented by different colours				Attribute (bottom level)	Additional explanation of attribute	Possible value 1	Possible value 2	Possible value 3
(1) BASIC INFORMATION	Tool				Consecutive number	Consecutive number in the catalogue.		:: Number	
					Name of DSS			:: Descriptive	
					Link to web page	Web page of DSS or DSS owner. Available only for DSS which are accessible online.		:: Descriptive	
					Owner of DSS	Institution or company who owns DSS.		:: Descriptive	
					◊ Country of development	Country where DSS was developed. *Marks assumed values - based on country of "Owner of DSS"		:: Descriptive	
					Country - tested	List of countries where DSS was validated.		:: Descriptive	
				Geographic focus	◊ Northern Europe	Based on (assumed*) "Country of development" and "Country - tested" Northern Europe: Denmark, Estonia, Finland, Latvia, Lithuania, Norway, Sweden.	Yes	No	
					◊ Central Europe	Based on (assumed*) "Country of development" and "Country - tested" Central Europe: Austria, Belgium, Czech Republic, Germany, Hungary, Ireland, Luxembourg, Netherlands, Poland, Romania, Slovakia, Slovenia, Switzerland, United Kingdom.	Yes	No	
					◊ Southern Europe	Based on (assumed*) "Country of development" and "Country - tested" Southern Europe: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, France, Greece, Italy, Kosovo, Malta, Montenegro, North Macedonia, Portugal, Serbia, Spain.	Yes	No	
(2) CHALLENGE	Scope				Plant protection	Scope of the DSS. Currently only plant protection DSS are included.		:: Descriptive	
	Constraints				◊ Space	Area of application of DSS. Values marked with * are assumed based on following rules: International: Multiple options under "Avaliable language" and/or "Country - tested" National: Single option under "Avaliable language" and/or "Country - tested"	National	International	
					Time	Timespan of aplicability of DSS. Definition of short-term for this purpose is a day, a week or a couple of weeks. long-term is for strategic purposes (e.g. a month, whole growth season etc.)	Short-term	Long-term	Both
(3) DECISION PROBLEM	Plant protection	Target crop types	Annuals	Arable crops	Cereals		Yes	No	
					Potato		Yes	No	
					Oil seed rape		Yes	No	
					Beets		Yes	No	
				Vegetables			Yes	No	
			Perennials		Fruit and berries		Yes	No	
					Vineyard		Yes	No	
					Grassland		Yes	No	
			Ornamentals				Yes	No	
			Other crops				Yes	No	
		Target pests		Diseases	*Septoria tritici* blotch		Yes	No	
					Potato late blight (*Phytopthora infestans*)		Yes	No	
					Apple scab (*Venturia inaequalis*)		Yes	No	
					Other diseases		Yes	No	
				Insects	Aphids		Yes	No	
					Cabbage root fly (*Delia radicum*)		Yes	No	
					Carrot root fly (*Psila rosae*)		Yes	No	
					Other insects		Yes	No	
				Weeds			Yes	No	
	Function	Monitoring				Monitoring of abundance of diseases, insects, and weeds.	Yes	No	
		Forecasting				Forecasting the abundance of diseases, insects, and weeds.	Yes	No	
		Planing				Planing diseases, insects and weeds management.	Yes	No	
(4) IMPLEMENTA-TION	Accessibility			Access	Access to DSS	Is DSS available online or offline?	Online	Offline	
					Login required	Does DSS require login?	Yes	No	
					Access to references		Yes	No	
				Language	Avaliable langugaes	List of available DSS interface languages.			
					National	National language of "(assumed*) country of development".	Yes	No	
					Available in English		Yes	No	
				Price	Free	Limited means there is free version avaliablewith limited functionalities or that limited number of people have free access (e.g. farmers from one country).	Yes	No	Limited
	Data required			Weather	Weather	Does DSS require weather data to operate?	Yes	No	
					Obtaining weather data	Method of obtaining weather data	Automatic	Manual	No
				Field data	Field observations	Observations from the fields such as pest abundance.	Yes	No	
					Date of sowing		Yes	No	
					Pre crop	Crop(s) grown on the field in the previous year(s)	Yes	No	
					Crop variety		Yes	No	
					Other data		Yes	No	
(5) APPLICATION	Users (direct)				Farmers	DSS is intended for use by farmers	Yes	No	
					Advisors	DSS is intended for use by farm advisors	Yes	No	
					Researchers	DSS is intended for use by researchers	Yes	No	
	Output				Map	DSS provides outputs as map.	Yes	No	
					Text	DSS provides outputs in textual description.	Yes	No	
					Numerical / categorical	DSS provides outputs in numerical or categorical values.	Yes	No	
	Scale of use					Number of users: Small (0-1999); Medium (2000-14999); Large (>15000)	Small	Medium	Large

Figure A1. Schematic representation of version 1.0 of the developed IPM-DSS typology and possible values of the attributes it contains. "::" indicates the type of value, not the value itself, while "◊" indicates attributes where assumed values may occur. All assumed values are marked with "*" in the IPM Adviser web tool.

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