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Unlocking crop protection models for decision support: web infrastructure and integration

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Abstract

Decision support systems (DSS) in crop protection provide valuable support for pest risk prognosis and recommendations for pest control, enabling farmers to make better-informed decisions. As a part of the European Union's strategy for the sustainable use of plant protection products, the "IPM Decisions" project developed an online platform that gives farmers and advisors access to a wide range of DSS for major pests, weeds, and diseases in a variety of crops across Europe. Multiple DSS models relevant for different crops and geographical regions of Europe were selected for integration in the platform. Information on the models is compiled into a model catalogue, which serves as a core component of the IPM Decisions platform. To facilitate the use of these models, two application programming interfaces (APIs) were developed. In line with the FAIR (findable, accessible, interoperable, and reusable) principles, the DSS API provides access to models and their metadata, including descriptions of input and output parameters. The weather API enables access to European online weather data sources and adapts this data to meet the requirements of DSS models. While these APIs are integrated into the IPM decisions platform, they are also open source, allowing other crop protection and farm management software to inspect, download, modify, install, run, and use them. In this article, we describe the development of the DSS and weather APIs, outline their structure and definitions, and present the services that DSS API and weather API provide. Finally, we demonstrate their application through three practical use cases.

Keywords: decision support systems, integrated pest management, crop protection modeling, application programming interfaces, model interoperability, FAIR principles, open-source digital platforms

1. Introduction

The European Union (EU) is committed to make agriculture more sustainable. Pesticide use within the EU is governed by the Directive for the sustainable use of pesticides (2009/128/EC) and further reinforced through initiatives such as Farm to Fork, Biodiversity strategy, and Green Deal (European Council 2021). IPM combines pest control strategies, methods, and tools to achieve better crop protection with less environmental impact, and its guiding principles can be dynamically applied to local situations (Barzman et al. 2015).

Successful crop protection at the farm level requires expertise and consideration of multiple factors, such as pest prevalence, potential crop loss caused by the pest, treatment cost vs. return of investment, uncertainty in crop response, pathogen resistance, weather conditions, and resource availability. Over the past decades, many decision support systems (DSS) with varying approaches have been developed. These systems assist decision-making processes in crop protection at operational, tactical, and strategic level, ranging from field to regional scales (Magarey et al. 2002, González-Domínguez et al. 2023). Typical questions addressed by the DSS include whether preventive or suppression measures are needed; how to schedule crop protection interventions; how to optimize pest monitoring programmes; whether and how to best carry out pesticide application (Rossi et al. 2019). Web-based DSS and their functionalities and limitations in disseminating IPM technologies were recently reviewed by Tonle et al. (2024). While individual studies report benefits of DSS use (Fabre et al. 2007, Jalli et al. 2020, Lázaro et al. 2021), their overall performance and value in real-world farming is difficult to quantify. DSS tools provide measurable benefits —such as economic savings, risk reduction, and lower environmental impact—as well as less quantifiable benefits, including enhanced situational awareness that supports proactive risk management (Evans et al. 2017).

Climate change is altering agricultural conditions, influencing crops as well as their associated pests (Sutherst et al. 2011, Lehmann et al. 2020, Lázaro et al. 2021). While new crops and cultivars are being introduced, pests are spreading into previously unaffected areas, and previously minor pests are becoming more prevalent. DSSs facilitate the transfer of knowledge from regions with experience in anticipated future conditions. However, any model's applicability to new regions requires thorough evaluation and testing.

Effective sharing of IPM decision-making tools has the potential to enhance the IPM implementation (Rossi et al. 2023). Sharing DSS models across national boundaries and in accordance with the FAIR guiding principles (findable, accessible, interoperable, and reusable) (Wilkinson et al. 2016, Barton et al. 2022) enhances their impact. Without interoperability and integration into local software solutions, these models remain underutilized, limiting the return on scientific and technological investments. The need to improve availability and interoperability of existing DSS models from multiple providers was a key driver for the EU funded IPM Decisions project (Ramsden et al. 2025). This initiative developed the IPM Decisions platform (platform.ipmdecisions.net), which offers DSS models in line with the FAIR principles. As the usefulness of any pest risk warning generated by a DSS model depends on the availability and quality of input data, we wanted to make it easier to integrate DSS models with weather data and other input sources. To achieve model interoperability and access to weather data, we created standardized web programming interfaces both for DSS models and weather input data. These interfaces—application programming interfaces (APIs)—can be accessed by any application that uses standard web protocols.

This article introduces two new APIs: DSS API, which provides structured information on DSS models and their metadata, and weather API, which manages weather data required as input to the models. The APIs act as an interface to a model metadata repository and a catalogue of weather data sources, and provide methods for their use. Standard ways were developed to store and deliver DSS information, and to collate weather input data. The APIs and their capabilities are a new digital infrastructure where information on multiple tested and validated DSS models for crop protection can be accessed in a structured way for direct use, testing, validation, and adaptation to local conditions. To our knowledge, these are the first open-source APIs that share validated DSS models across multi-national environments and provide models with weather input data at a European scale.

Section 2 presents through two use cases the design choices and specifications of the DSS model catalogue and APIs, and defines the concepts used. Section 3 presents the implementation, and Section 4 presents three application examples.

2. Design of the DSS model integration framework

Modern agricultural software is fragmented, with different services used across Europe. Transferring DSS models from one DSS solution to another and integrating them with weather data or other input data is challenging due to heterogeneity: models originate from different providers, require varied input formats, and produce outputs that differ in structure and interpretation. These inconsistencies hinder interoperability and limit scalability. To address these challenges, we developed a standardized framework for model and weather input data integration as part of the free and open IPM Decisions platform (platform.ipmdecisions.net). This work was preceded by a systematic collation and prioritization of DSS models available to the platform (Nistrup-Jørgensen 2020). Our design aims to support not only the IPM Decisions platform but also external client applications, enabling DSS providers to leverage shared resources while maintaining their own user interfaces.

Given the rapid evolution of agricultural technologies, future use cases of this framework cannot be fully anticipated. Therefore, the architecture emphasizes flexibility and extensibility, ensuring that new models, data sources, and client applications can be integrated with minimal effort. Design choices are illustrated through two use cases.

2.1 Farmer and adviser use case

John is a crop manager who wants to know if disease pressure in his wheat crop has risen above the threshold value, or if he can safely proceed without spraying fungicide. First, he opens his user application and enters crop information (crop and location). The application lists suitable models to be accessed; John selects one. The application then asks for model input information, namely sowing date and cultivar resistance, and John specifies them. As he first mistypes the date, the application prompts him to correct it. For the possible weather data sources provided, John selects one from a list and requests the application to calculate disease pressure. Behind the scenes, necessary weather data is fetched, formatted to fit the model requirements, and cumulative disease pressure for the given crop is being calculated. The application then presents the result to John as a graph with illustrative symbols, confirming John's perception of low disease pressure.

2.2 DSS provider use case

Jill, a software developer employed by a large agricultural advisory organization, wants to add their prognosis model to the model catalogue so that the model can be easily accessed by farmers. The IPM Decisions Platform Board was in favour of including it, as it was already validated for use in two European countries and described in a peer-reviewed scientific publication. Jill goes to the designated GitHub repository, and follows the protocol outlined there. Using the provided tools, she composes model information, integrates it to the model metadata repository, and tests that the model works as intended.

2.3 Definition of concepts

Decision support system (DSS): In this article, DSS refers to software application or service that assists decision-making by applying models or algorithms to generate actionable recommendations. One DSS can contain one or more models (or DSS models).

Metadata: Descriptive information about data or models. Metadata facilitates data discovery, validation, and interoperability.

Interoperability: The ability of different systems, applications, or components to exchange and use information in coordinated manner, achieved through standardized formats, protocols, and interfaces.

Schema: A standardized definition of data structure (e.g. JSON schema) that ensures interoperability and allows validation of data against its expected format.

Application Programming Interface (API): An interface, based on a set of rules and protocols that enable software components to communicate and exchange data, allowing integration between different systems or applications. APIs are fundamental building blocks as they allow developers to connect systems or components without managing underlying complexity.

API endpoint: A specific URL or resource within an API that performs a defined function, such as retrieving data or executing an operation, serving as the access point for interaction with API.

Catalogue: A structured repository that lists available records (e.g. decision support models or weather data sources) along with their metadata, enabling discovery, comparison, and integration into applications.

Amalgamation (weather data): The process of combining weather data from multiple sources or formats into a unified dataset, ensuring consistency and compatibility for use in decision support models.

Source ranking (weather data): The process of prioritizing weather data sources based on pre-defined criteria, to select the most suitable input for decision support models.

2.4 Main components of the framework

2.4.1 Catalogue of DSS models

The catalogue of DSS models stores structured descriptions of decision support system (DSS) models that are accessible through the IPM Decisions platform (platform.ipmdecisions.net). Schema definitions in the catalogue specify how model metadata, input, and output are structured, validated, and exchanged. For each model, the repository contains both human-readable and machine-readable information. Model records include target crops and pests, geographic validity, model input parameters (types/units, defaults, steps, and min/max), required weather parameters with logging intervals, output structure and presentation guidance, and the URL of the model's own API.

Conceptually, the information stored in this catalogue supports filtering and discovery of models (e.g. by crop, pest, or area of validity), establishing the communication with the model APIs, preparation of model input data, and interpreting the model response. Human-readable information can be used to help end users to assess the relevance of the model to their specific needs, whereas machine-readable information enables client applications to construct valid input data sets and correctly interpret model results. The catalogue is dynamic and designed for easy integration: adding new models or updating metadata should only involve minimal effort for client applications.

2.4.2 Catalogue of weather data sources

The catalogue of weather data sources is a structured list of meteorological data providers that can supply the inputs required by DSS models. An important part of the catalogue is the schema definition that enables describing and converting weather data from different sources. The catalogue characterizes various weather data providers: national meteorological institutes, international services, and private weather stations. Different categories include for instance *in situ* observations, reanalysis datasets, and forecasts. Descriptive metadata is stored in the catalogue: for instance, spatial/temporal resolution, geographic coverage, and parameter availability.

Conceptually, the information stored in the catalogue supports discovery of a weather data source based on a given region and parameter set, ranking data sets by their quality and relevance, processing of weather input data using predefined conversion models or other methods, and adapting data from different sources to model's input requirements. The catalogue is dynamic: new providers can be added and metadata refined, allowing adaptation to evolving open-data policies and increasing observation density and model resolution across Europe.

2.4.3 APIs and services

Access to models and model-ready weather inputs is operationalized by two web programming interfaces. The first one, the DSS API, exposes the catalogue of DSS models: it returns model metadata and schemas, validates inputs against the schema definitions, and provides testing capabilities. It allows client applications to select a model, construct valid inputs, communicate with the model's own API, and interpret outputs consistently. The other interface, the weather API, exposes the catalogue of weather data sources; assembles, adapts, and quality-controls weather data; and delivers model-ready time series in the schema used by the models.

2.5 Interaction of the components

At a high level, the architecture contains four interacting elements: (i) The catalogue of DSS models (model descriptions and schemas), (ii) The catalogue of weather data sources (sources and descriptions for weather data), (iii) The DSS API

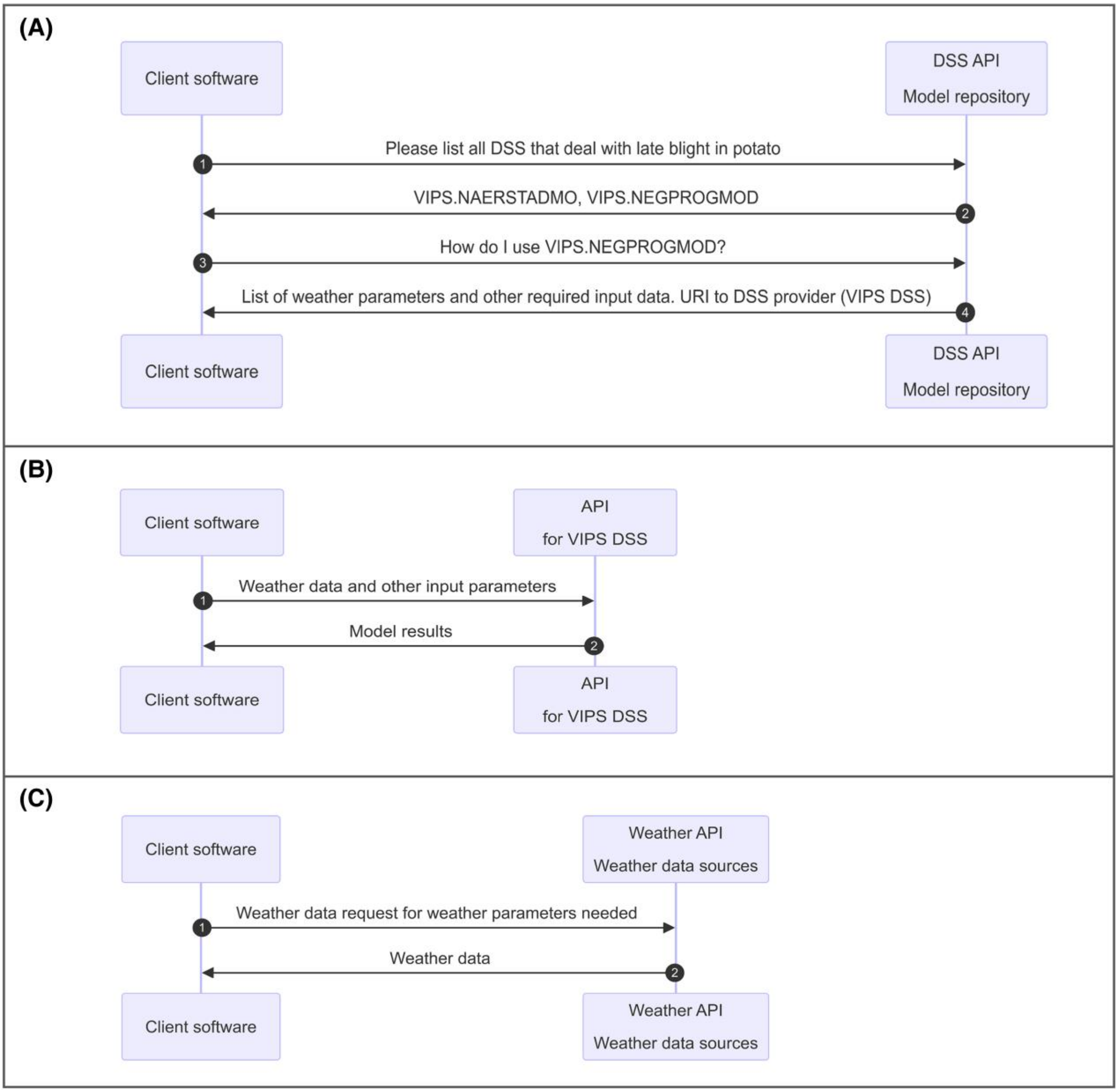

Figure 1 Communication flows for client software. (A) Use of DSS API to select a DSS model (1–2) and prepare for communication with the selected DSS model (3–4). (B) Retrieval of model results. VIPS is used as one example of several DSSs. (C) Requesting weather input data that is needed by the DSS model.

(gateway for model discovery, input validation, schema retrieval, and conformance testing), and (iv) The weather API (gateway for weather data source discovery, production of model-ready inputs, adaptation, and weather data processing).

The client applications can query the DSS API to discover suitable models, fetch schemas, and validate inputs. For model-specific weather data requirements, the client can either (i) call the weather API's service to receive best-available input data, or (ii) explicitly select a source from the catalogue of weather data sources. The client then composes input data and submits an execution request to the model's own API (as referenced in the model catalogue), and renders outputs following the model's output schema and presentation guidance. Figure 1illustrates the sequence of model selection, input preparation, and result retrieval.

2.6 How the system supports the use cases

Farmer and adviser use case (John): John uses software (user application) that communicates with the DSS and weather APIs. The DSS API acts as an interface to the model catalogue and enables model search (e.g. by crop, pest, and location), input validation (e.g. sowing date ranges and cultivar resistance), discovery of weather data requirements, communication with the selected model, and output interpretation. The weather API acts as an interface to the catalogue of weather data sources; adapts weather data to match the selected model's input schema, and returns model-ready weather data for input. The user application can therefore warn John on invalid inputs, automate weather retrieval, and render model outputs consistently.

DSS provider use case (Jill): A new model record is added to the model catalogue with all schema-required fields (for instance: targets, descriptions, region of validity, inputs, weather requirements, output definitions, and the model's own API). The DSS API's testing functions verify that the model operates as expected. After Board approval, the model is published and becomes discoverable and executable via the APIs.

3. Implementations

3.1 Implementation of IPM decisions DSS API

3.1.1 Overview of DSS API services and endpoints

The DSS API (Skog 2024) provides a searchable catalogue of available DSS models. Use of the DSS model metadata repository and its schemas is arranged through fixed API endpoints. Figure 1A illustrates a simplified example where client software uses the DSS API to select a DSS model, and subsequently prepares for communication with the chosen model. The client software prepares the required model input, and Fig. 1B illustrates a simplified example of retrieving model results from the selected DSS model. As the model is interfaced by its API (here the API for VIPS DSS) and all interaction uses web protocols, the details of model implementation are not exposed to this interaction.

Endpoints of the DSS API are organized in three functional groups:

- DSS service—provides a searchable catalogue of available DSS models.
- Metadata service—defines and manages data structures. This includes endpoints for schema definitions, and validation services for model input data.
- Admin service—offers administrative functionality, which is restricted to internal users. Examples include returning CSV-formatted data to initiate DSS translation processes when integrating new DSS into the platform.

Commonly used endpoints are detailed in Table 1, and links to full documentation and description of deployment on a server platform are provided in the Supplementary Material. In the code the abovementioned service names are written without spaces (e.g. MetaDataService).

Target crop types and target pests for DSS models are identified within these services at varying levels of hierarchy. The DSS API employs the international coding system maintained by The European and Mediterranean Plant Protection Organization EPPO (EPPO 2022), which includes codes for relevant target crops and pests, their scientific and common names in multiple languages to support trans-national use, and a separate API for dynamic use of the code database.

3.1.2 DSS models

The model catalogue provides access to metadata for all DSS models that are linked to the IPM Decisions Platform. The catalogue stores information on whether the integration of a model to the platform is full, partial, or linked (Ramsden et al. 2025). The type of integration defines whether the model can be employed through the provided APIs (full and partial integration), or if the user accesses it through a link directly to the DSS provider. Models can be added to (or removed from) the repository as needed. The list of DSS models available is dynamic, as new DSS and their models can be added to the catalogue without changing the DSS API. Table 2 lists the fully integrated models available at the time of writing. Up-to-date information can be requested from the DSS API using web service endpoints in Table 1.

The selection of DSS models for implementation in the platform is based on an overall aim to make a wide range of DSS models available for testing and use through the IPM Decisions platform, promoting a collaborative approach for resource sharing among developers. A 'gold standard' has been defined for models developed by reputable DSS developers and researchers, tested, validated, and widely used over many sites and seasons, with results published in peer-reviewed journals (Ramsden et al. 2025). However, it is not a requirement to meet all these criteria for a DSS model to be available through the IPM Decisions platform. Once a DSS model is identified and ready for implementation, the IPM Decisions Board will ensure that the model originates from reputable developers and researchers and that further information on the model is provided to enable informed choices on its use. Resources for model deployment (also portrayed earlier in DSS provider use case) are provided in the Supplementary Material.

Table 1 List of important web service endpoints in the DSS API.

Service	Endpoint path	Description
DSS	/rest/dss	List all DSS's and models available in the platform
DSS	/rest/dss/{DSSId}	Get all information about a specific DSS
DSS	/rest/dss/crop/{cropCode}	Returns a list of DSS's that are applicable to the given crop (identified by EPPO code)
DSS	/rest/dss/pest/{pestCode}	Returns a list of DSS's that are applicable to the given pest (Identified by EPPO code)
DSS	/rest/model/{DSSId}/{ModelId}	Metadata for a DSS model in the default language. Adding language parameter (for instance, '?language = no') to the path results in the translated version.
MetaData	/rest/schema/dss	Returns the complete structure of metadata as defined in the Json schema.
MetaData	/rest/schema/dss/yaml/validate	Takes DSS metadata in YAML format as input, and validates it against the Json schema provided in the/rest/schema/dss/endp

For all end points and their full documentation, refer to resources in the Supplementary Table S1.

Table 2 Fully integrated DSS models available on the IPM decisions model catalogue at the time of publication, indicating DSS model name, purpose, pest, crop and model source.

DSS model name	DSS purpose	Pest	Crop	Source	References
Large Narcissus Fly Model (Warwick HRI)	Estimates the timing of Large Narcissus Fly activity	Narcissus bulb fly	Narcissus species	WarwickHRI	Collier and Finch (1992), Phelps et al. (1993)
Pollen Beetle (Warwick HRI)	Estimates the timing of Pollen Beetle activity	Pollen Beetle	Cauliflower; Broccoli; Oilseed rape	WarwickHRI	Phelps et al. (1993)
Cabbage Root Fly (Warwick HRI)	Estimates the timing of Cabbage Root Fly activity	Cabbage root fly	Brassica family	WarwickHRI	Collier and Finch (1983a), Collier and Finch (1983b), Collier and Finch (1985), Finch and Collier (1983), Finch and Collier (1985), Finch et al. (1986), Phelps et al. (1993)
Carrot Fly (Warwick HRI)	Estimates the timing of Carrot Fly activity	Carrot fly	Carrot; Parsnip; Celeriac; Parsley	WarwickHRI	Phelps et al. (1993), Collier et al. (1994), Collier and Finch 1996
Cutworm Model	Estimates the risk of cutworm larvae surviving to third instar	Cutworm	Lettuce; Beets; Potato; Brassica; Carrot; Parsnip; Allium; Chicory; Asparagus; Celery; Tomato; Strawberry	IPM Decisions	Bowden et al. (1983)
Orange Wheat Blossom Midge Emergence Model	Estimates risk of emergence of adult Orange Wheat Blossom Midge	Orange blossom midge	Winter Wheat; Spring Wheat; Rye; Barley; Oats; Triticale	IPM Decisions	Jacquemin et al. (2014)
Pollen Beetle Migration Model (simplified)	Estimates risk of pollen beetle migration	Pollen Beetle	Oilseed rape	IPM Decisions	Ferguson et al. (2016)
Saddle Gall Midge Model	Estimates risk of emergence of adult saddle gall midge	Saddle gall midge	Wheat; Rye; Barley; Oats; Triticale	IPM Decisions	Rowley et al. (2017)
Codling moth flight model	Estimates risk of start of codling moth flight and egg laying	Codling moth	Apple; Pear	IPM Decisions	Damos et al. (2018)
BYDV TSUM model	Estimates risk of virus transmission by aphid vectors	Barley Yellow Dwarf Virus	Winter Wheat; Winter barley	IPM Decisions	AHDB 2022
Hutton Criteria Late Blight Model	Estimates risk of late blight	Potato late blight	Potato	IPM Decisions	Dancey et al. (2017)
Grey Field Slug (Cereals)	Threshold for control measures	Grey Field Slug	Winter Cereals	IPM Decisions	Glen (2005a), Glen et al. (2006)
Grey Field Slug (Oilseed Rape)	Threshold for control measures	Grey Field Slug	Oilseed rape	IPM Decisions	Glen (2005b), Glen et al. (2006)
Carrot fly flight model	Estimates risk of flight and egg laying	Carrot fly	Carrot	VIPS	Markkula et al. (1998), Tiilikkala and Ojanen (1999), Markkula et al. (2000)
Cabbage fly flight			Brassica family	VIPS	

(*continued*)

Table 2 Continued

DSS model name	DSS purpose	Pest	Crop	Source	References
model (Scandinavia)	Estimates risk of flight and egg laying	Cabbage root fly			Johansen and Meadow (2005, 2006)
Cabbage moth model	Estimates risk of damage by Cabbage Moth	Cabbage armyworm	Brassica family	VIPS	Johansen (1997)
Nærstad model	Daily risk of infection	Potato late blight	Potato	VIPS	Hjelkrem et al. (2021)
Alternaria TOMCAST	Daily risk of infection	Potato early blight	Potato	VIPS	Madden et al. (1978)
Negative prognosis	Estimates risk of Late Blight infection	Potato late blight	Potato	VIPS	Ullrich and Schrödter (1966)
Onion downy mildew DOWNCAST	Weather-based infection risk alerts	Downy mildew of onion	Onion; Allium species	VIPS	de Visser (1998)
Downy mildew of grapevine	Estimates Downy Mildew infection risk	Downy Mildew of grapes	Grapes	Gaiasense	Orlandini et al. (2008)
Septoria Humidity Model	Estimates risk of septoria	Septoria leaf blotch; Glume blotch; Tan spot	Winter Wheat; Wheat	SEGES DSS models	Jørgensen et al. (2020)

Further details on each model are available in the model metadata and by contact with the model source organization.

Table 3 DSS model metadata sections in DSS model metadata repository.

Section	Content
Human-readable description	Title, purpose, description, authors etc.
Categorizations for filtering	Valid crops and pests described by EPPO codes, spatial validity described by country list and by geographic polygons
Execution description	Type of model (fully/partially integrated, or just a link), Json schema definition for input data, and web service endpoint for execution
Weather input data description	Required weather data parameters and their sampling frequency (hourly, daily etc.)
Output data description	How to interpret the risk status returned by the model, metadata for displaying results in a chart

3.1.3 Model metadata, translations, and schemas

In the catalogue, each model is described in two complementary ways. The human-readable form is describing the model purpose and functionality to support well-informed decisions regarding its applicability. The machine-readable form enables client applications to supply the required input data and correctly interpret the model outputs. Metadata for each DSS model contains the sections listed in Table 3.

The catalogue supports multi-lingual use, and translation of metadata is performed by plant protection experts. The process includes converting the existing metadata to a human-readable work file and after translations are completed converting the result file into a Java properties file. These conversions are performed using Python scripts located in the metadata repository. The human-readable description in the metadata for each DSS is stored in the default language only. Translations are stored as Java ResourceBundles and provided on-the-fly from the DSS-Service endpoints when the language parameter is part of the web service request (see example earlier in Table 1).

Categorizations for filtering include crops, pests, and geographic validity of the model, enabling the API to query and suggest appropriate models. A JSON schema specifies both the standard input data, such as required weather data parameters and log intervals, and model-specific features. The schema is crafted by or at least supervised by the DSS owner to ensure that all parameters are clearly defined in terms of type or unit, default values, value steps, and max/min values. Field observations of pests represent a special case among model-specific features, as models tend to require very specific and diverging quantifications of the observations as inputs. Thus, custom JSON schemas for the quantifications are necessary.

3.2 Implementation of IPM decisions weather API

3.2.1 Overview of weather API services and endpoints

The weather API (Skog et al. 2024) manages creation of weather input data for the models behind the DSS API. It provides a searchable catalogue of weather data sources and supports

Table 4 Examples of web service endpoints in the weather API.

Service	Endpoint path	Description
Amalgamation	rest/amalgamation/amalgamate	Try to get all the requested parameters for the given location in the specified period. The service tries to fix QC failing data, missing data, and data that needs to be calculated.
WeatherDataSource	rest/weatherdatasource/location/point/	Weather data sources and their parameters at a given location. Location (for instance '?latitude = 60.8&longitude = 23.5') to be added to the path.
WeatherAdapter	rest/weatheradapter/fmi/	Get weather observations in the IPM Decision's weather data format from the Finnish Meteorological Institute https://en.ilmatieteenlaitos.fi/ Access is made through the Institute's open data API: https://en.ilmatieteenlaitos.fi/open-data

For all endpoints and their full documentation, see resources in the Supplementary Material.

Table 5 Weather data sources currently recognized by the weather API.

Weather data source[a]	Region	Historic/forecast	Grid/station network
Norwegian Meteorological Institute (https://www.met.no/)	Global	Forecast	Grid
Met Éireann (https://www.met.ie/)	Ireland	Forecast	Grid
Danish Meteorological Institute (https://www.dmi.dk/)	Denmark	Historic and forecast	Grid
Swedish Agricultural University Meteorological Network (https://www.slu.se/en/faltforsk)	Sweden	Historic and forecast	Grid and stations
Deutscher Wetterdienst (https://www.dwd.de/)	Germany	Forecast	Grid
Finnish Meteorological Institute (https://www.ilmatieteenlaitos.fi/)	Finland	Forecast	Grid
Agrometeorological Service of Norway (https://lmt.nibio.no/)	Norway	Historic	Stations
Meteobot (https://meteobot.com/en/)[b]	Global	Historic	Stations
Fruitweb (https://www.fruitweb.info/en/)[b]	Global	Historic	Stations
METOS (https://metos.global/en/)[b]	Global	Historic	Stations
Météo Concept (https://www.meteo-concept.fr/)[b]	France	Historic	Stations
Open-Meteo (https://open-meteo.com/)[c]	Global	Historic and forecast	Grid

[a]The availability of data from each of the providers, such as available parameters, spatial and temporal resolution may change over time.
[b]Access to private weather stations will require login details.
[c]Open-Meteo is an open-source weather API and offers free access to weather data from multiple national weather services for non-commercial use.

both discovery and pre-processing of their data. Figure 1C illustrates a simplified diagram for requesting weather input data needed by a DSS model. The weather API provides both forecast and historical data, available as point measurements from weather stations and as gridded datasets. The weather API is designed to be flexible; it can adapt both to the improving open data policy among the European Meteorological Institutes and to the increasing number of observations and fine scale models. This way the weather API takes advantage of pre-processing (data assimilation and quality control (QC) of observations), numerical weather prediction (NWP), and post-processing by the National Meteorological Institutes, e.g. open and publicly accessible download services from Norwegian Met. Institute (Müller et al. 2017, Båserud et al. 2020, Nipen et al. 2020, Lussana et al. 2023).

The endpoints of the weather API are organized in six functional groups:

- Weather amalgamation service—composes weather input data and fixes potential gaps or problems.
- Weather data source service—provides a catalogue of available sources for weather data.
- Weather adapter service—converts weather data from a specific source into the required format.
- QC service—performs QC of weather data.
- Metadata service—enables querying of meta data.
- Test data service—supplies test datasets for validation and integration purposes.

A list of commonly needed web service endpoints is presented in Table 4. In the code, service names are written without spaces (for instance, WeatherDataSourceService).

3.2.2 Weather amalgamation service

The weather amalgamation service serves as a common entry point designed to provide best fitting weather data for the user's needs by leveraging available weather data sources (Table 5). For a given location, weather data is automatically selected using source ranking information (see Fig. 2). Source ranking is derived from the metadata associated with each weather data source and

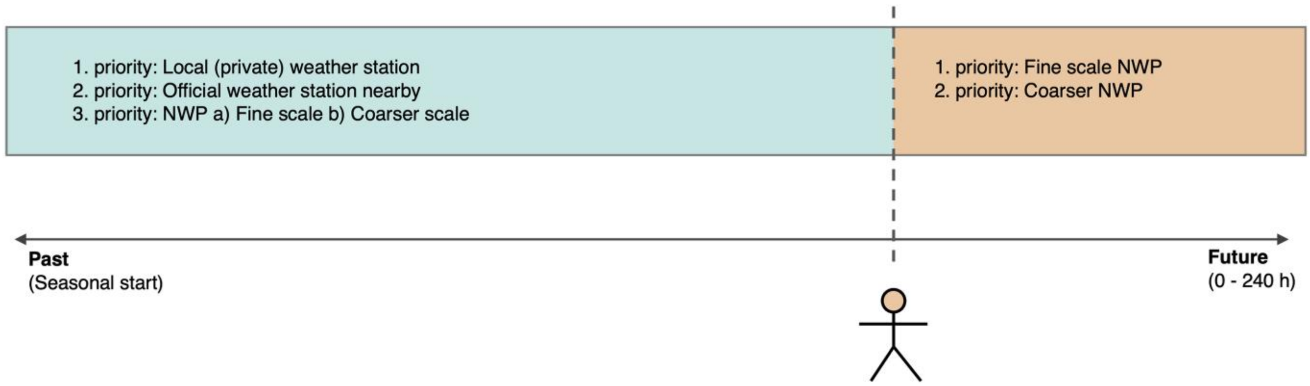

Figure 2 Source ranking. At any European location (lat, long) the actor gets the presumable best weather data needed for the DSS in question. The Amalgamation service of the weather API delivers the first choice of each parameter following this priority list.

is fully documented in the released source code (see Supplementary Table S2). For example, observational data from weather stations are generally ranked higher than NWP output. For past and present weather data, NWP data may be used to fill temporal gaps between observations for one or more parameters. The ranking is partly location-dependent, as spatial resolution, temporal resolution, update frequency, and post-processing quality may vary across data sources and regions.

The weather amalgamation service can also perform additional processing steps to build the requested data set. For example, Leaf wetness measurements are rarely available from public weather services and are therefore calculated when required. Two models, LWLSTM (Hjelkrem et al. 2026) and RH90 (Sentelhas et al. 2008), both validated for European conditions in Hjelkrem et al. (2026), are integrated into the weather amalgamation service for leaf wetness estimations. The LWLSTM model, which depends on relative humidity, rainfall, temperature, and wind speed, is prioritized due to its better performance and strong robustness. If any of these parameters are unavailable, the RH90 model, which requires only relative humidity, is used.

In addition, if temperature data are missing, the service attempts to fix gaps in the time series using simple linear interpolation, limited to a single missing value. For use cases requiring full transparency regarding data origin and the processing of weather parameters, users may bypass the amalgamation service and instead select data directly from a specific weather data source.

3.2.3 Weather data source service

The weather API connects to multiple weather data sources. Reliable, open-access sources for gridded weather analysis and forecasts exist for all parts of Europe, though with different scales ranging from 7 km grid spacing (or more, depending on time scale) down to 1 km and even downscaled to sub-km grid spacing in some areas for nowcasting purposes and short-range forecasts. Both measured data, (re)analysis and forecasts are available, from international services, national services, and private weather stations. Reanalysis provides spatially and temporally consistent historical reconstructions of meteorological variables. The main source for reanalysis in Europe is 'Copernicus European Regional Reanalysis' (Ridal et al. 2024). These datasets, as well as other weather sources used by the weather API, are disseminated by providers listed in Table 5.

3.2.4 Weather adapter service

While the weather amalgamation service and some of the weather data sources deliver data in the standard format mentioned above, adapters are available for sources that do not. These adapters download weather data and transform it into the correct format for the DSS models, and are available from the weather adapter service.

3.2.5 Metadata service

Weather data retrieved from online sources can be used for models in the DSS API by using the IPM Decisions standard JSON format. The schema and the validation service for weather data are provided by the Metadata service, which also supplies lists of the weather parameters and QC codes.

3.2.6 QC service

QC of observation data is an essential part of weather data management. Observations produced by national meteorological institutes are generally handled through detailed QC systems and are therefore considered as quality controlled, whereas data from private weather stations may vary in terms of data control. Prior to use in a DSS model, data from sources with uncertain control routines are processed using a basic QC system (QC service). The QC consists of a logical test and specified interval, step and freeze tests, for which threshold values can be set separately.

3.2.7 Test data service

Test data service supplies test datasets for validation and integration purposes.

4. Application examples

4.1 IPM decisions platform as user of the DSS and weather APIs

The IPM Decisions platform (Ramsden et al. 2025) is a web-based framework providing farmers, advisors and researchers access to a wide range of validated DSS models and weather data from across Europe through a set of four dashboards. Figure 3 shows an example of how model results are presented in the user dashboard. The DSS and weather APIs are primarily

Figure 3 User dashboard of the IPM Decisions platform. Results for a winter wheat model are shown in form of a bar chart, line chart, and explanatory text.

developed to serve this platform and consequently, the platform dashboards are the main users for the APIs.

The platform is initiated when users register, log in, and provide background information for their farms. For each farm, users specify the location and crops, and select the DSS models for specific pests they wish to follow during the growing season. The platform then updates model statuses daily using the newest weather data retrieved from the weather API. Users can get an overview of the model outputs and warnings for their crops at any time. The dashboards also enable comparisons between models, simulations with historical data, and experimentation with model parameters. The interaction of the platform with the DSS and weather API is displayed in Fig. 4.

The platform uses the DSS API services to retrieve information from the DSS model metadata repository and related microservices. When users enter crop details, the platform requests the DSS API for available models relevant for their specific crops and locations. The model input schema stored in the metadata repository describes the required inputs, enabling the platform to request the API for necessary information and automatically create web forms for the dashboard where users are prompted to provide the required parameters.

To improve and simplify user experience, the platform utilizes the weather amalgamation service within the weather API. This service automatically identifies the best weather data sources for each farm location and the requested weather parameters, handles any necessary format modifications and applies methods such as interpolation to refine the weather data before sending it to the model. Additionally, users can integrate their own private weather stations from external providers by entering their login credentials and weather station details. When this option is selected, the platform calls the weather amalgamation service with the user's station details. If any parameter is missing, the system will supplement it with data from the primary sources provided by the weather API. Finally, when model results are returned, their representation in the user dashboard follows the model output schema provided by the DSS API. This schema specifies how to structure and present results for each integrated model.

4.2 Integration of a DSS in other webservices; VIPS as a user case

The Norwegian pest prediction platform VIPS (www.vips-landbruk.no) is an online forecast and information service for decision support in integrated management of pests, diseases, and weeds. The VIPS platform is open-source and has been recognized by the UN as a global digital public good (Liang et al. 2023). The VIPS web, targeting Norwegian agriculture, is developed and managed by NIBIO in collaboration with the Norwegian Agricultural Extension Service.

The integration of the saddle gall midge (Haplodiplosis marginata) model for use in VIPS presents an example on how a crop protection software outside the IPM Decisions platform can use these APIs to implement individual DSS models. The main approach of this integration is to make a model of interest available for test and validation through a service familiar to the Norwegian users. Saddle gall midge is a significant pest in many cereal-growing regions of northern Europe, which

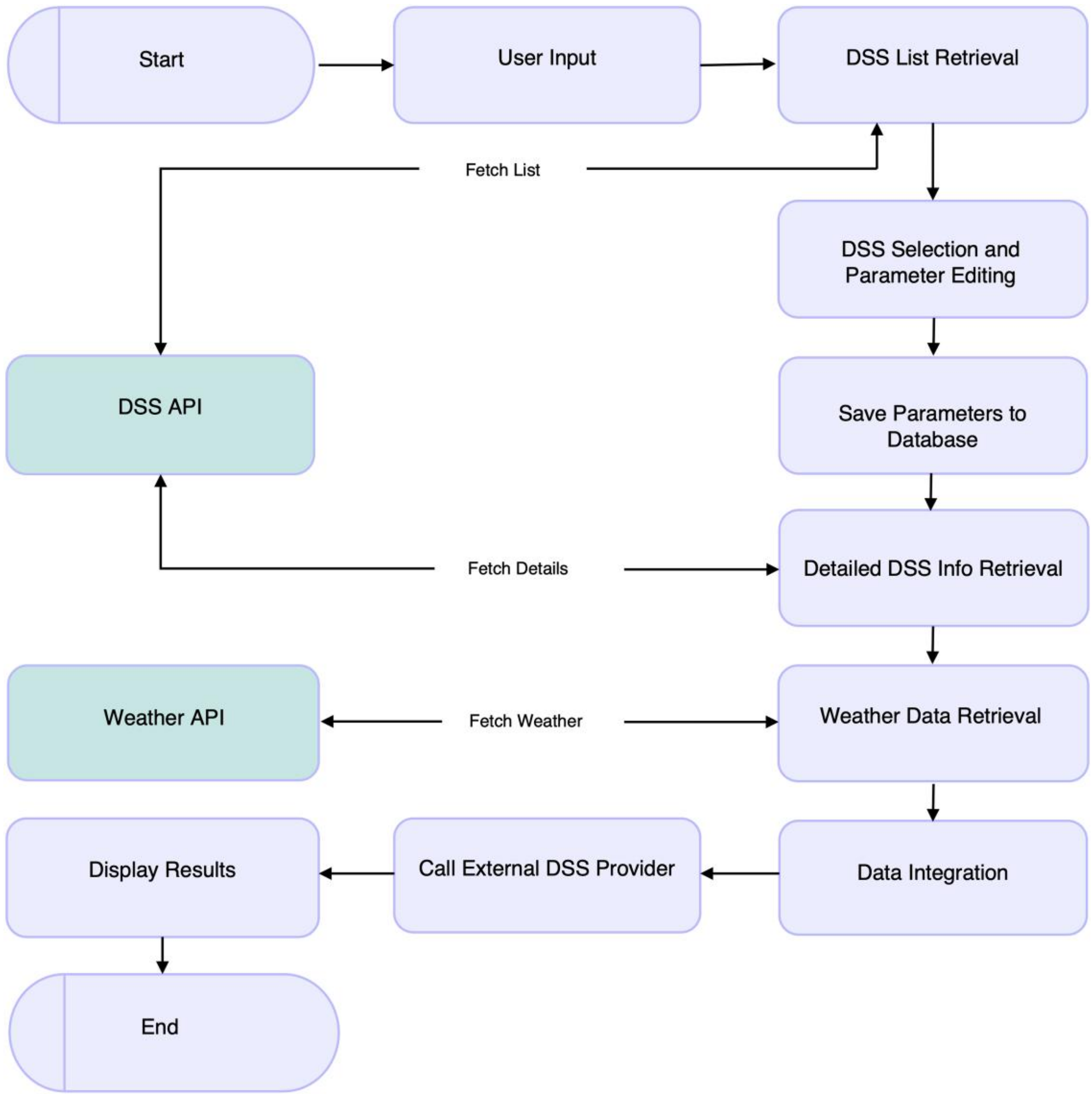

Figure 4 IPM Decisions platform flowchart. Integration with DSS and weather API.

makes it interesting to provide the model for testing. The user interface (Fig. 5) presents an interactive form where the users can select weather data and enter model input data, such as start and end dates for modelling.

An external DSS (external to the IPM Decisions platform) such as VIPS can add a DSS model from the IPM Decisions platform by using the DSS API, optionally in combination with the weather API. A DSS model in the platform includes machine-readable metadata describing its essential characteristics, enabling client software to integrate the model with a minimum of code. Once the client code has been created for one model, the addition of more models will require only minor adjustments. In addition to this example and increasing interoperability for the models, several VIPS models are now shared to other users through the DSS APIs of the IPM Decisions model repository.

4.3 Integration in Python and in OpenAlea: research-targeted modelling platform

A set of Python packages has been developed to interact with IPM Decisions resources directly from the Python language, without requiring knowledge of the underlying web services. These packages provide a functional Python API to access weather data and run DSS models. Packages are open-source and available from GitHub and Conda. They are deeply integrated with the OpenAlea modelling platform, allowing researchers to compare DSS models with their own models, develop, and test models in different conditions, and combine with their own production.

The Python library consists of three packages built on top of IPM Decisions web services. These services provide access to weather data catalogue (weather adapter service), weather data sources (weather data source service), and associated metadata (Metadata service) together with DSS catalogue (Metadata service for DSS) and DSS calling endpoints (DSS service). The first package (Agroservice, https://github.com/H2020-IPM-openalea/agroservice) allows transparent use of IPM decisions web services from Python, with minimal transformation of web service responses. The two other packages (WeatherData and DSS) allow to convert textual information returned by agro-services into high level Python objects. These handle weather data (i.e. managing units, localization,

Figure 5 Illustration of how a DSS model from the IPM Decisions platform is integrated in the VIPSweb. (A) Model description, input data, and optional parameters for the DSS. (B) Weather data sources. (C) Output graph. The source organization for the Saddle Gall Midge Model is ADAS, UK.

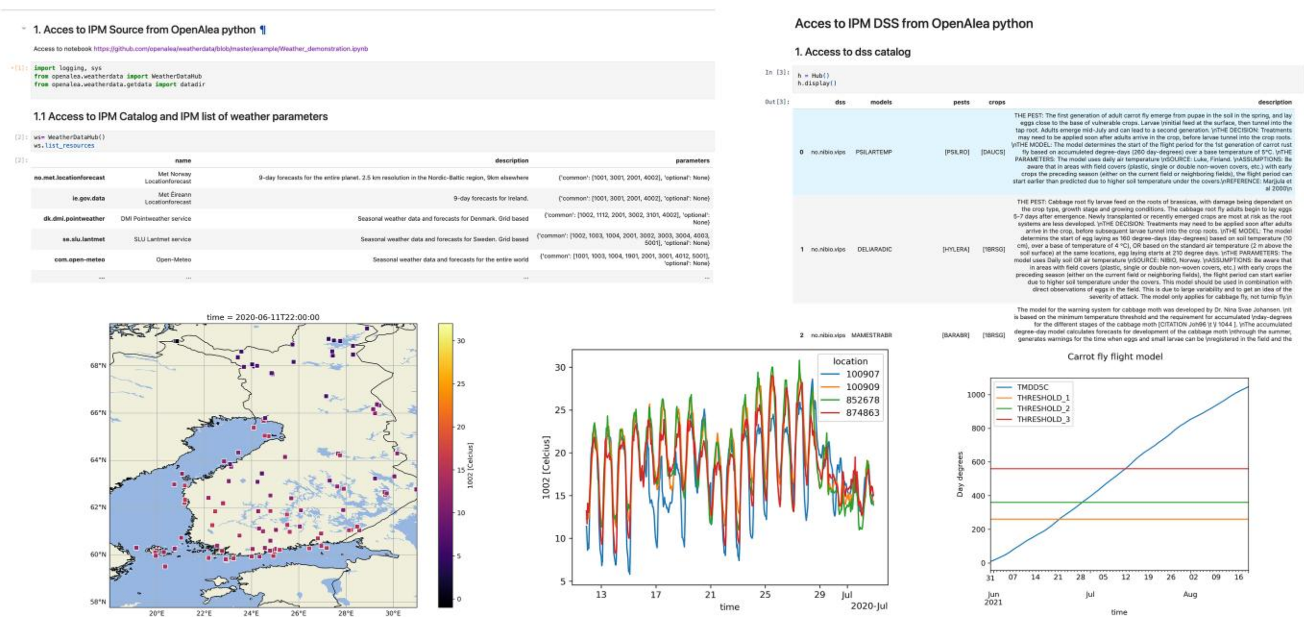

Figure 6 A Jupyter notebook tutorial for weather data and DSS.

and metadata) and models (i.e. managing metadata and formal descriptions). Figure 6 illustrates an example of a Python script executed in a Jupyter notebook. Both WeatherData and DSS packages are further integrated into VisuAlea, the visual programming environment of the OpenAlea platform (Pradal et al. 2008) that allows using and exploring the same resource in a visual programming environment (see Fig. 7).

5. Discussion and conclusions

This paper presents the development and functionalities of new APIs for crop protection models and their weather input data management. The DSS API provides model metadata, data structures, and tools that facilitate the use of DSS models. The weather API enables preparation of the weather input data for DSS models, including access to European weather services, dataset conversions, and data management. While these APIs are part of the IPM Decisions platform, they also serve external users. Both the DSS and weather APIs are open-source and published under GNU Affero GPL v3 license, to promote the use of IPM in agriculture. Links to resources are provided in the Supplementary Material.

Current DSS platforms are commonly designed for specific user groups or regions, and depend on local weather data, which limits their broader applicability. The APIs presented

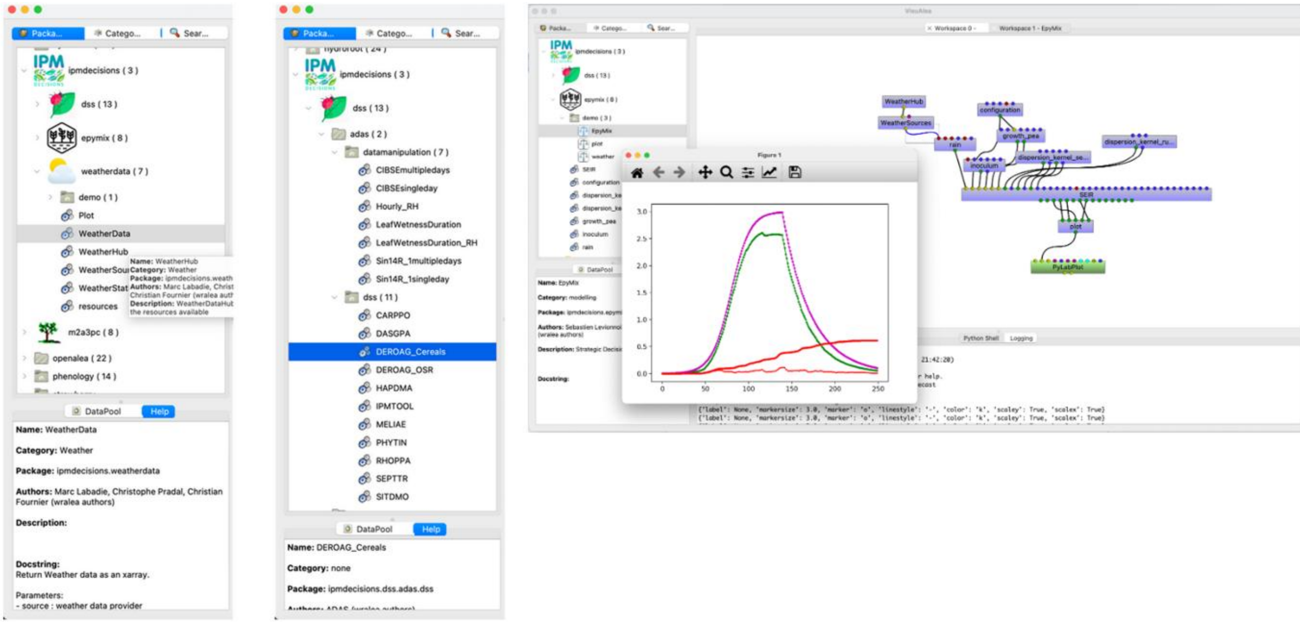

Figure 7 OpenAlea and VisuAlea integration. The resources of the IPM Decision platform are available through Python and in the package manager of OpenAlea. On the left, weather data services can be added using drag and drop, and their metadata are displayed. In the middle, the user can select all the DSS models, read their metadata, drag and drop them in VisuAlea and run them. On the right, two models provided by VIPS are connected to the same weather data sources.

here address this limitation by enabling wider use and extending the usability of various DSS models beyond their original regional context, thus opening opportunities for testing, validation, and direct application in new environments. These models, often built on decades of fundamental research with practical applicability as a priority for developers (Gent et al. 2013, González-Domínguez et al. 2023), become more valuable when made accessible to growers and available for further research and development. The work presented here enhances how models can be discovered, accessed, understood, and re-used by providing a well-documented digital infrastructure that supports integration with weather input data. The APIs not only enable comparison and testing, fostering knowledge accumulation and transparent decision support, but also demonstrate operational value by already serving hundreds of users in the EU through dedicated online services presented here as application cases. We anticipate that further exploration and adoption of these APIs will drive new successful implementations, as increasing usage is a key to maintaining and sustaining the system's existence.

In software design, APIs are essential for connecting systems without exposing underlying complexity (Tan et al. 2016). The DSS API and weather API follow the REST architecture (Fielding 2000), a widely adopted approach for web services that enables developers to share functionalities and to build upon existing solutions (Richardson and Ruby 2008). This server–client approach is common in weather data provision and has been successfully applied in pest development simulation and meteorological time-series generation (Fortin et al. 2022). Commercial platforms such as Agrio (https://agrio.app/Agriculture-API/) and iMetos (https://metos.global/en/disease-models/), and the Norwegian free and open VIPS platform demonstrate how APIs can be utilized in the context of delivering DSS models. Such environments support efficient testing and development by enabling reuse and extension of existing work.

While these APIs address technical interoperability and accessibility, their impact ultimately depends on the broader ecosystem where the DSS models are used and how the ecosystem evolves. The implementation logic of DSS platforms is shaped by the availability of public funding, the stakeholders involved, and the sustainability of underlying business models. Publicly available platforms such as the Norwegian VIPS (www.vips-landbruk.no), the Italian DSSs for viticulture (Bregaglio et al. 2022), or the new European IPM Decisions platform (Ramsden et al. 2025) can operate effectively without paywalls, provided that governments or other actors ensure sustainable financing. In contrast, commercially driven solutions—such as those offering hardware like local weather stations combined with data services, often integrate DSS models to deliver added value for their customers. Danish Crop Protection Online CPO (Rydahl 2003) is focused on weed control and serves as an example of a commercial DSS offered by an advisory organization. Many systems blend public and commercial aspects; for example, in the network for environment and weather applications (NEWA;Carroll et al. 2017) that is focused to serve fruit orchards, DSS tools are publicly developed and the joining states or institutes cover operating costs, but access may require purchasing commercial weather stations (Pinto et al. 2025).

Approaches behind the decision support models for crop protection are evolving, which may influence the need and use patterns of these APIs. Current advances in automatic detection, identification, and prediction of pests and diseases underline the potential of AI and machine learning in pest management (Domingues et al. 2022). Machine learning has provided high success rates in plant disease detection (Ferentinos 2018, Zhao et al. 2024), and is noted for provision of a powerful framework to assimilate data (Ip et al. 2018). In deployment of machine learning approaches, mechanistic or empirical models such as the ones provided by the DSS API may be useful to constrain the outcome to biophysical limits.

Combining plant disease models, plant growth models, and fungicide models (Rossi et al. 2019, González-Domínguez et al. 2023) is one of the relevant emerging approaches for developing decision-making tools. New approaches can support the integration of different computational models through reverse engineering (Midingoyi et al. 2023) or by coordinating parallel execution across diverse programming languages and operating systems (Lang 2019). Bregaglio et al. (2025) present a recent Italian public initiative where eight disease models for grapevine downy mildew were implemented and their outputs integrated with a phenology and susceptibility model. Overall risk level was computed using machine learning (Random Forest algorithm), and all model outputs were then prompted to a large language model that prepared the communication of model results to the growers.

The DSS API architecture presented in this article is versatile and could—for instance—be combined with large language models that would further communicate model outputs to growers as in the work described in Bregaglio et al. (2025) and Calone et al. (2025). Implementation of features such as orchestrating multiple models, aggregating outputs, or representing uncertainty is not provided, but may be developed for instance through the Python interface provided by the OpenAlea application. Approaches could be designed and implemented by the user, as the current architecture allows for instance running simulations with parameter variations, or using simulated weather datasets. However, the existing deployment is not made for thousands of concurrent sessions or simulations due to memory and resource constraints, and performance also depends on the capacity of individual DSS providers. If the APIs were to be used in this way, some architectural changes would be required to support scalability and high-speed data access.

Farm management information systems (FMIS) could be key future users of these APIs from the farmer's perspective, although we currently lack application examples. FMIS are a common way for farm enterprises to manage, document, report and optimize their production processes (Fountas et al. 2015, Tummers et al. 2019, Saiz-Rubio and Rovira-Más 2020). In the EU, FMIS are highly relevant for agricultural operations, offering support for documenting agricultural activities, managing nitrogen balances, facilitating subsidy applications, and, in some instances, assisting with crop protection decisions (Munz et al. 2020, Melzer et al. 2023). The FMISs hold source data for DSS models (fields, soils, management dates, connections to weather stations, etc.) and could streamline the documentation needed to prove compliance to IPM-based decision making, as required by the common agricultural policy rules or the commercial supply chain. To facilitate integration to FMIS, interoperability and integration frameworks could be effective, but given the lack of consensus among the FMIS service providers, fixed APIs like the ones we here provide seem to be the best approach for the interested FMIS to adapt to. APIs also align with the current evolution of smart systems and devices in agriculture (Antle et al. 2017, Zhai et al. 2020).

Adoption of the APIs has begun strongly through the IPM decisions platform: by May 2024, 970 user accounts were registered, representing 1282 farm locations across Europe (Ramsden et al. 2025). Most accounts (60%) were in the UK, Netherlands, and Denmark, with advisors forming the largest user group (35%). This highlights the platform's role in professional decision-making and its potential to influence farm-level practices.

Despite these promising results, limitations remain. Model coverage is uneven across regions, and applicability is restricted for some crops and production systems. Future progress depends on sustainable funding and further development or integrations to drive user adoption. Addressing these challenges will position the IPM Decisions DSS API and weather API as key enablers of data-driven, sustainable crop protection across Europe.

Keeping the continuity and high standard is a challenge for years to come. There is a protocol for offering and approving DSS models to the repository, and new open weather data sources can be added to the catalogue. This system consolidates scattered information on DSS models and weather data to improve usability for end users across the EU, ultimately supporting the goal of sustainable agriculture.

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Supplementary material

Supplementary material is available at *in silico Plants* online.

Conflicts of interest

None declared.

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Data availability

The DSS and Weather API described in this study are open source. Source code, metadata schemas, and documentation for the APIs are available through public repositories under open-source licenses. The catalogues of DSS models and weather data sources are implemented as structured metadata repositories and are accessible programmatically through the API endpoints. These metadata include model descriptions, input and output schemas, and weather data source characteristics. Weather data are accessed dynamically from third-party data providers and are subject to the respective providers' terms of use. Repository links and links to documentation are provided in the Supplementary Material.

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