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Precision Agriculture: Modelling

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https://doi.org/10.1007/978-3-031-15258-0_16

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Abstract The development of the Akkerweb service platform (https://akkerweb.eu) was started around 2010. It is an open platform in precision farming, providing the maps, services, data, and connections required, in principle, for any smart farming application envisioned. This includes background maps, services for weather data, satellite images, soil maps, crop polygons, etc., but also visualization tools, an app store, a task map generator, and crop growth models. Akkerweb provides the infrastructure needed to develop an application easily using the available services and to publish it on the Akkerweb platform. Moreover, Akkerweb applications can also run on other websites, seemingly as stand-alone applications with the look and feel of the customer's website.

A unique point of the Akkerweb service platform is the availability of several science-based agronomic models which are currently made available as APIs for use in smart farming applications. Examples of these models are those to calculate water availability (Watbal model), potato crop growth (Tipstar model), late blight infection (Blight module), and nematode management (Nemadecide) at individual field and within-field levels. Other models are available for variable-rate application of soil

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D. Cammarano et al. (eds.), *Precision Agriculture: Modelling*, Progress in Precision Agriculture, https://doi.org/10.1007/978-3-031-15258-0_16

herbicides and fungicides against blight, nitrogen top-dress application in potato and potato haulm killing. In total, Akkerweb has more than 30 apps.

farmmaps (https://farmmaps.eu) is the next version of Akkerweb. It has a new data repository and management system as well as a new, more intuitive dashboard design running on all devices. It became available first in 2021.

Abbreviations

AWS	Amazon web services
CI	chlorophyll index
FMIS	farm management information system
GIS	geospatial information system
GPU	graphical processing unit
ICT	information and communications technology
NSS	nitrogen side dress system
UAV	unmanned aerial vehicle
WDVI	weighted difference vegetation index

1 Introduction

Precision agriculture (PA) is a farming management concept based on observing, measuring, and responding to inter- and intra-field variability in crops (Wikipedia, 2020). It is expected to lead to an increase in productivity and quality, as well as increased sustainability (Van Evert et al., 2017a, b). Adoption of PA is slower than expected because it is complex to apply, among other issues (EIP, 2015). Kempenaar et al. (2018) listed at least 13 different PA applications in potato production. All these PA applications have data, a decision support, and an actuation component and cannot be carried out without information and communications technology (ICT). Many hard- and software tools have been developed and marketed in the last 25 years to capture data on variation in crops. The technologies enable measuring and viewing of site- and time-specific soil, crop, climate, and input and output variables and using these data in operational, tactical, and strategic decisions. To start with, a farmer must have a suitable farm management information system (FMIS) (Fountas et al., 2015) to use the data. The FMISs have developed from simple crop-recoding software tools on stand-alone computers to web-based database platforms with geo-spatial information system (GIS) features and connections to data suppliers. In the Netherlands, we identified at least 25 of such platforms in arable farming. They are marketed by different types of institutions such as advisory, sensor, crop protection and fertilizer companies, machine companies, farmers' cooperatives, and knowledge institutes. The Wageningen University & Research also developed such a platform in cooperation with the Agrifirm Plant, a farmers' cooperative, and DOBS automatisering, a software company, with the aim of developing decision support for precision faming as close as possible to Dutch farming practices and to work as much as possible with the state-of-the-art of data that are available on farms.

In this chapter, we describe the development of the Akkerweb and **farm**maps precision agriculture service platforms. In Sect. 2, we give a brief history and technical implementation and features of the platforms and in Sect. 3, a selection of models and apps that can be used on the platforms. We end in Sect. 3 with an outlook on how data platforms will contribute to mature data-driven precision agriculture.

1.1 Development of Akkerweb and farmmaps Platforms

The development of Akkerweb was set in motion by two projects more than 10 years ago. The first was a pilot developed for *Boerenbond Helden*, a farmers' cooperative that needed a GIS to match tenants with landlords. The prototype system depicted one's own fields as well as fields available for rent. Requests could be made by interested farmers to open these fields for review, presenting all necessary information, such as soil type, fertilization history, cropping scheme, diseases, etc. The second initiative came from the NemaDecide project (Been & Schomaker 2004; Been et al., 2005) and the development of a decision support system (DSS) for potato cyst nematodes and root knot nematodes, both quarantine organisms. This required a geographical component identifying the field and the exact location and dimension of the sampled areas, regardless of being disease free or infested, to produce the correct advice needed to manage these pests.

The Wageningen University & Research joined forces with Agrifirm Plant, a farmers' cooperative, in 2010 to develop a service platform for precision agriculture, named Akkerweb. Software programming was done by DOBS. By 2016, the partners concluded that Akkerweb was mature enough to be launched on the Dutch market as an open service platform for precision agriculture. Users can create an account for no charge in which they can manage public and private data, do crop monitoring, and apply precision agriculture applications, for example, to make variable-rate prescription maps. Today Akkerweb has over 5.000 users, mainly Dutch arable farmers, farm advisors, and researchers. It has undergone several technical modifications, and currently, Akkerweb 3.0 named **farm**maps with a new data repository and management system with a new, more intuitive dashboard design, has become available in 2021.

1.2 Features of the Platforms

Akkerweb is a cloud-based service platform on which apps provided by different developers can run. It provides basic apps and services (e.g., weather data) together with many specific applications. Table 1 provides a list describing the services and features that are available to every user, while Table 2 lists the applications Akkerweb provides free of costs. These are considered the basic instrumentation every user and developer needs. The landing page and dashboard of Akkerweb are shown in Fig. 1.

Table 1 List of services and features freely available to use

Feature	Description
Account grower	Akkerweb offers an individual login for accounts; this means that only the user (grower) has access to the files he owns. Via "single sign-on," the user is directly logged into other services and applications that are relevant for him/her; this avoids repeated entering of user account credentials
Background maps	Displaying geographical information against a freely chosen background: Google maps, OpenStreetMap, Bing, Top10, or any other background
Crop polygons	Can be downloaded using various web services, directly from the Dutch government (RVO) or by public reference map layers of crop fields (most EU countries)
Contact details	Once entered, data are available in all applications the grower wishes to use
Downloading or drawing fields	Fields can be uploaded from Dutch FMIS CROP-R and CropVision (upload xml message) or added using drag and drop. (formats supported: Shape files, Google polygons, etc.). If necessary, crop polygons can be drawn by hand
Crop cultivation data	If not available by upload from an FMIS, Akkerweb provides a simple crop rotation app to provide advisory systems with cropping information (crops, varieties, planting date, growing period)
Sensor data	Tractor logs, data via .csv, .xlsx, .dbf, .dat, but also satellite data (NVDI, WDVI, yield maps (geotiff)) can be uploaded. Addition of a new format will take half a day
Editing	Standard functionality for editing geographical information; edit, merge, or split fields, add objects, and convert grid files and other formats into visual information
Links	Web services to agro partners are available, a.o. ISAcert, Eurofins, WEnR, NEO, Dacom and AgroVision. VanderSat, Agrirouter, etc
Storage	All data remain property of the grower/owner and can be used or stored for later application. Data are stored on Amazon AWS in Ireland
Output	Generic output is possible. As .csv file, as .pdf for pictures, etc. this functionality is available to each application
Applications	The grower can use the free and the commercial applications with the plot as his starting point

(continued)

Table 1 (continued)

Feature	Description
ISOBUS, shape, and surfer	Task maps can be generated for ISOBUS, shape, and surfer format
Sharing information	Growers can share their geographical information, time-limited if necessary, completely or partially, with third parties (neighbor, cooperation, or payroll employee
Send/retrieve data	Edi-crop v 4.0 and the eLab messages are supported. Using services to business management systems prevents repetitive data input
Uptime and scalability	The Akkerweb platform is hosted on Amazon servers under European law. This ensures an uptime of almost 100% and instant scalability (number of users) and provides the need for fast processing of geographic data
Weather	Available are 40 years of historical data (30 by 30 km grid) and observed and forecasted weather (500 by 500 m) worldwide. Rain radar information is included for the Netherlands
Available information and models	Availability of soil maps, crop growth models, etc. crop polygons from 2009–now, agricultural acreage 2013

Table 2 Freely available Akkerweb applications (apps)

App	Description
Cropping plan	Entering grower's fields plus crops, cultivars, soil type, planting, and harvesting date either manually or via web services connecting to official bodies and farm management systems.
Map	Overview of all of a grower's fields on a map. Add layers of information from your applications, for example, all fields that have been sampled, all fields with sensor data, etc. click on a field polygon and all information available will be listed.
Sensor data	Upload all types of sensor data and visualize the information. Use these data in various applications on Akkerweb.
Satellite	Download satellite imagery – WDVI and NVDI biomass maps for further use in Akkerweb, for example, haulm killing (currently WEnR and NEO WCS services).
Contractor	Order sensor information, EM38 (v/d Borne), Veris scan (Agrometius) and NVDE, and WDVI drone images (dronewerker.nl) directly from Akkerweb, and receive the results in your account.
My advices	Advice generated in the advisory apps used by third parties and not available to the farmer can be stored and retrieved for later use.
Charing information	Connect with another Akkerweb user and share information in different ways (time bound, editable or not, etc.).
Store	Here all available applications can be found and downloaded to the account holders desktop, application can be for free, licensed, sponsored, etc.

Akkerweb apps can be integrated in several ways within the framework. In its most simple form, a third-party app runs in an i-frame and can be found in the Akkerweb Store and added to the dashboard if needed. The next step is an external

(a)

(b)

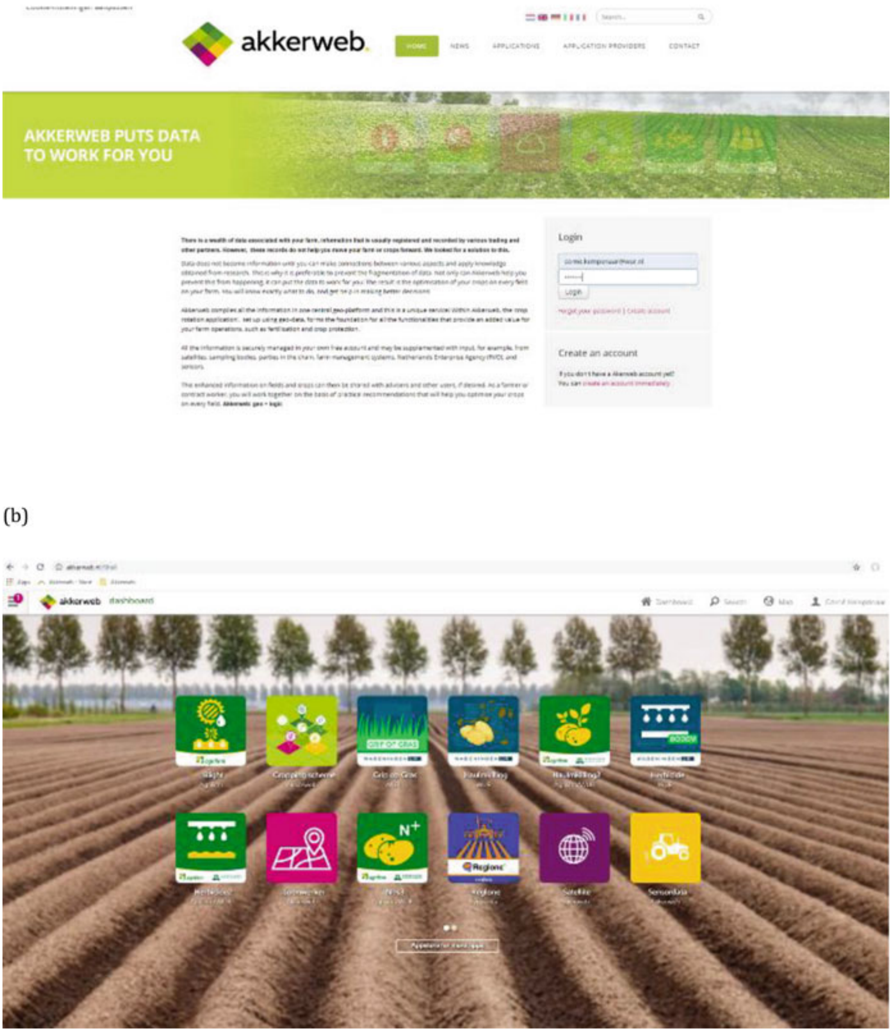


Fig. 1 Impression of Akkerweb 2.0. (**a**) Landing page and (**b**) a user dashboard

app that uses some of the services (Akkerweb APIs), for instance, the farmer's cropping scheme, but has no connection to the other apps. When fully "integrated," Akkerweb apps can share their information with other apps. For example, new layers generated by a fully integrated app are available for use by other apps.

The data model of Akkerweb is the reference model Agro (rmAgro) developed by Goense (2017). This standard facilitates the connections with other platforms, portals, and agribusiness companies that comply with rmAgro for laboratory results, cropping schemes, advice, and cultivation messages (e.g., fertilizers, irrigation, crop protections, and yields).

Several functions and services are encapsulated in Angular software components and can easily be added to a new app. Developers can now concentrate on the desired interface and implementation of their own knowledge. In **farm**maps, using Angular by default, a component library is available with interface objects that can be reused.

1.3 Technical Implementation

Akkerweb is a web-based platform based on a client-server architecture. There are currently two generations of Akkerweb applications, using a slightly different technology stack.

1.3.1 Authentication/Authorization

Akkerweb uses a claim-based authentication and authorization scheme; user identities are provided in the API requests as JSON Web Token (JWT), provided by an OpenID Connect compliant identity server.

1.3.2 Server Side

The business logic of the first generation was implemented in .Net C# using the NetTopology suite for the spatial operations. Some computation-intensive parts were offloaded to parts implemented in C / C++ on a CUDA server. The server side of second-generation Akkerweb applications is also implemented in C# (.Net Core), but NetTopology suite has mostly been replaced with GDAL (GDAL/OGR contributors, 2021).

1.3.3 Server Side, Data Persistence Layer

Akkerweb runs on Amazon AWS servers under European law. It also allows for robust availability and scalability. Amazon was chosen specifically because only its servers were equipped with GPUs for graphical calculations. Most of the Wageningen University & Research apps run on Amazon, but app developers can also run their apps on their own servers.

Apps can run on Akkerweb and can be stand-alone. A digital request for soil sampling for instance runs on Akkerweb, where it is connected with the crop polygons of the farmer, but is also on the website of the soil sampling agency offering this service. Data persistence is implemented using a Postgres/Postgis database server for the meta-data.

1.3.4 Client Side

The client side of Akkerweb applications of the first generation is implemented in a multiple page pattern using JavaScript and HTML5/CSS supported by toolkits as jQuery, Knockout js, and OpenLayers 2. Applications of the second generation are implemented as a SPA (single page application) using Angular 9+, typescript, HTML5 /CSS, bootstrap 4, and OpenLayers 3+/Cesium. Cesium is used for the 3D visualizations.

1.3.5 Client Server Communication

In Akkerweb applications, all communication (between the client and the server and between applications) is based on RESTful services with the payload formatted as Json/GeoJson. Most geographical data are transported following different OGC standards such as WMS, WFS, WMTS, and WCS, but in the APIs, a GeoJson-based representation is used. SignalR on a WebSocket transport is used for push communications (events).

2 Models and Apps on Akkerweb/farmmaps

There are currently more than 30 apps available on Akkerweb. See Table 3 for an overview of the most used apps. Some of these are Akkerweb apps which are free for use and provide basic functionality. The other apps are provided by WUR and external partners who use the platform to enable their applications. Some agro-ecological models in webservices are linked to Akkerweb and **farm**maps. Hereafter, we describe two models and five apps that run on Akkerweb and **farm**maps. The models deliver information on soil and crop status to the apps.

2.1 WatBal Soil Moisture Balance Model

WATBALsig is a simple water balance model for an unsaturated or saturated soil profile. It is derived from the WATBAL model (Berghuis-van Dijk, 1985) which was primarily developed to produce dynamic hydrological data, such as moisture content, over a long time scale for a separate agricultural nitrate leaching model. Vinten (1999) used WATBAL to simulate nitrate leaching from soils with different textures. These qualities make WATBAL suitable for other modeling purposes such as irrigation advice and grass or crop growth prediction (see Sect. 3.4.2, Chap. 3).

Complex agro-hydrological models for predicting moisture content like SWAP (Kroes et al., 2008) have the disadvantage that rather detailed input is needed. The

Table 3 List of WUR and third-party applications available in the Store

Application name	Short description
Digital sampling request	Nematodes, phosphate, and white rot
Stripbuilder	Program to subdivide fields into sampling units for nematodes, phosphate, white rot, tracks, and buffers, in order to supply sampling maps and display results
NemaDecide Geo	Free version of a decision support system for the potato cyst nematode
NemaDecide Geo PLUS	Version of NemaDecide including root knot nematodes (*Meloidogyne chitwoodi*) and the root lesion nematode (*Pratylenchus penetrans*) with extra features
Agrifirm mineral	Calculate fertilizer needs, based on crop, soil type, and acreage for your whole farm
AgrifirmGBM	Calculate crop protection product needs, based on crop, soil type, and acreage for your whole farm
Task map nematostats	Based on soil sampling results, a task map will be calculated including official delimitation
Potato information	More than 400 potato cultivars and all their properties, including partial resistance against potato cyst nematodes, blight, etc., data querying and links to the breeders
Task map haulm killing	Biomass-dependent haulm killing of potatoes based on NDVI and WDVI originating from satellite and E-bee
Task map side dress nitrogen	Biomass-dependent task map for nitrogen side dress for potatoes based on NDVI and WDVI originating from satellite, E-bee, or Yara images
Task map herbicides	An application map based on lutum (clay particles <2 μm) and organic matter content of the soil
Get hold of your grass production	Measure your grass height georeferenced using your mobile and calculate the Feed Wedge on Akkerweb
Bioscope	A service that provides a farmer with different products, among which is an WDVI-green biomass map, every 10 days. Imagery originates from satellites or from drones, when satellite images are unavailable
Late Blight	A completely new state-of-the-art decision support system to avoid yield losses by *Phytophthora infestans.*
Task map Blight treatment	The late blight app can be extended with the variable-rate app
Task map lime application	Calculate task map for site-specific need for potassium based on pH map (Veris sensor)
Grip on Data	Drop word, excel, and pdf files on your plot and make them georeferenced. Click on your plot and have a look at all your plot data
Mycokey App	Comprehensive monitoring of mycotoxins at critical control points in the food/feed chains for wheat and maize (DON, Aflatoxin B1, and Fumonisin)
Tipstar	Crop growth model for potato (growth is limited by the availability of water and nitrogen)
WatBalSig	Dynamic prediction of moisture content depending on precipitation, evapotranspiration, irrigation, and drainage
GAOS	Calculate the optimal driving path of your tractor over the field, avoiding obstacles, and download it to your tractor
Zoning	Read in sensor data for your field, calculate treatment zones, and make a task map yourself

precision and very small time-step (≫ 0.1 day) with which they describe the water balance are superfluous compared to the precision that is needed to simulate crop transpiration on a daily basis depending on soil moisture content and practical precision farming purposes. Therefore, a model is required that describes the water balance of a soil profile more globally. Such a model should meet the following demands (adapted from Berghuis-van Dijk (1985)):

- Input of only the most important soil characteristics
- Good simulation of water balance of the root zone, from which crop transpiration is subtracted at a rate which is affected by soil moisture content
- Good simulation of movement of the groundwater table, which is a condition for simulating boundary water fluxes and a proxy for judging the quality of water balance simulations
- Quantification of real evapotranspiration, capillary rise, drainage (subsurface), irrigation, and upward and downward seepage, which are important for correct simulation of the soil water balance and management
- Short computing time for facilitating real-time interactive exchange with the user and the possibility of developing a future self-learning system for enhancing simulation quality

The WATBAL model simulates the water balance of a (cropped) soil in a simple and fast way, dividing the soil profile into two layers. The first layer represents the root zone and the second layer the subsoil to at least the depth of the deepest groundwater table. The model calculates analytically on a daily basis per sub-time step (≤ 1 day) the changes in moisture content of the two layers and the movement of the groundwater table. Calculations depend on precipitation, evapotranspiration, capillary rise from layer two to layer one, water transport from layer one to layer two, and possibly drainage to differently defined drainage systems (including a bottom boundary).

WATBALsig is developed from WATBAL by implementing some new features and adaptations to meet the specific requirements for the intended use of the model. The most important of these are the following:

The dependence of crop transpiration on soil moisture is described with the well-known Feddes model (Feddes et al., 1978)

The first layer is divided into a root zone with dynamic depth and a zone without roots

The model is made more robust for special conditions such as perched groundwater (layer one saturated and layer two unsaturated)

For precision farming purposes, WATBALsig has been made operational by a user interface that runs on Akkerweb/**farm**maps (Fig. 2). To arrange field-specific input, the web application provides weather data and the crop concerned from Akkerweb/**farm**maps and soil data and hydrologic features from digital geographic maps of the Wageningen University & Research, department Environmental Research. The next step is to build into WATBALsig all kinds of precision farming Internet devices.

Fig. 2 WatBal provides the water requirement related to the crop grown, here potato. The dark line represents the calculated water requirement of the crop that should be maintained at the "Enough" level. Currently, water requirement can be calculated for more than 10 major crops and, when using weather prediction, irrigation advice, and both the amount and time to apply, can be provided

2.2 *Tipstar Water- and Nitrogen-Limited Potato Crop Growth Model*

Tipstar is a potato-specific model that simulates crop growth, soil water dynamics, and nitrogen dynamics for crops and soil. It was originally developed to support decision-making in starch potato production (Jansen, 2008) and has recently been updated (Van Oort et al., 2020). The model is unique in that growth of the canopy takes precedence over growth of other organs. Thus, tuber initiation and growth of potato tubers take place when more assimilates are created than are needed for canopy growth. In adverse growing conditions, assimilates can be remobilized and translocated from the tuber to the canopy.

Tipstar-based recommendations for the application of nitrogen and irrigation water lead to yields similar to those obtained by the best farmers (Jansen et al., 2003). In spite of this, the model has not found practical application, possibly because of the effort required to gather input data, perform simulations, and present results in a meaningful way.

In 2020, Tipstar was integrated into Akkerweb 3.0 where soil, weather, and crop management information can be provided. Now, the user can use a mouse to indicate on a map on the computer screen the field(s) for which Tipstar should simulate production. The location of the field is used by Akkerweb to retrieve weather data and biophysical properties of the soil. Planting date, maturity class of the cultivar, irrigation dates and amounts, and the dates and amounts of fertilizer application can be provided by the user or retrieved from the user's farm management information system (FMIS). With this information, Tipstar produces time series of several important variables that describe the status of the soil (e.g., water content profile, N content profile) and crop (e.g., LAI, leaf biomass, canopy biomass, tuber biomass) (Fig. 3).

Tipstar as offered on Akkerweb 3.0 supports tactical and operational decisions about the application of fertilizer and/or irrigation water by providing in-season information about the crop and soil. For an in-season decision, a mix of current weather, forecast weather, and historic weather is used. Current weather is used up to the day of the decision (e.g., 15 June 2020), and forecast weather is used for the next 2 weeks (16–30 June). The rest of the year (from 1 July until harvest) is simulated stochastically: 30 simulations are performed, where each simulation uses the weather of one of the last 30 years. This results in a plume of curves rather than a single

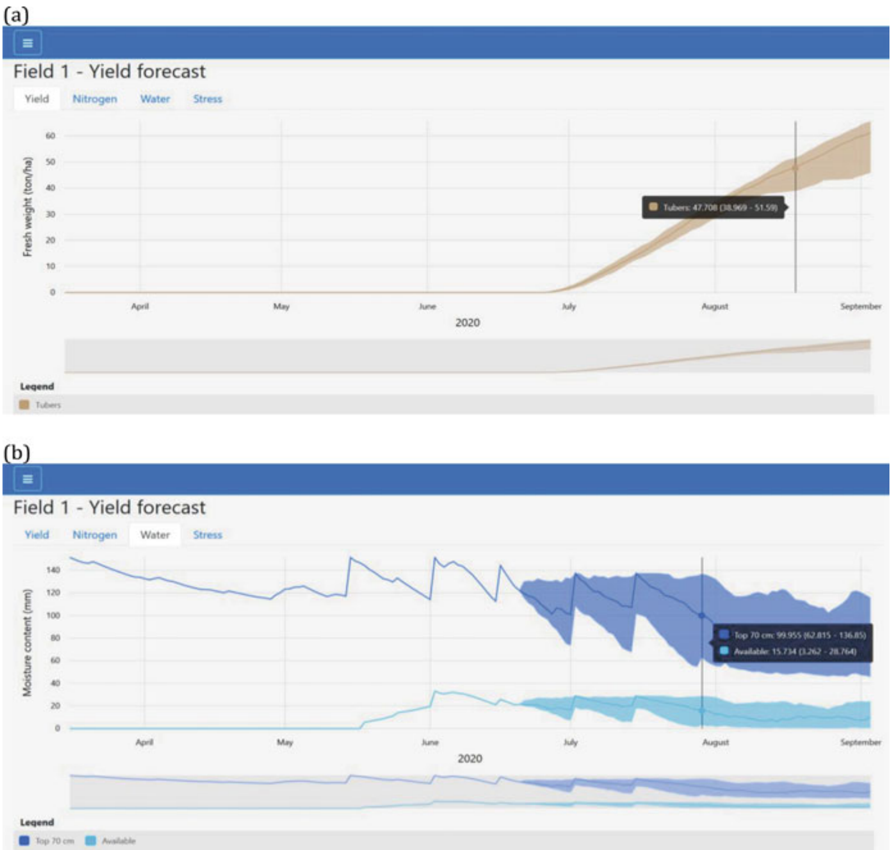


Fig. 3 Tipstar forecast for a potato crop near Wageningen. (**a**) Fresh tuber yield. The crop was planted on 15 April 2020 and the forecast was made on 4 June. From planting to 4 June, observed weather was used for the simulation. For the 2 weeks following 4 June, forecast weather was used. From 20 June, a stochastic simulation using 30 years of historic weather was performed; thus, from 20 June, the line becomes a plume. (**b**) Total amount of water in the upper 70 cm of the soil and plant available water. The figure shows that the crop will run out of water with the irrigation schedule that is proposed

curve; the median of the curve is taken as the expected value, and the spread around the median indicated the uncertainty of the simulation. Once a field has been registered, Tipstar is run every day, and the application creates an alert when the simulation indicates that N or water will become limiting to growth within the next few days.

2.3 NemaDecide

NemaDecide is a DSS for the management of plant parasitic nematodes that started as a PC version (Been et al., 2004, 2005) but has now been converted to an Akkerweb application. Models for population dynamics, yield reduction, partial resistance, soil sampling, chemical control, etc. are included in the system. It combines several data sources and models to enable strategic and operational decisions at the farm level (see Fig. 4a, b). The quantitative information system provides growers with the possibility to estimate risks of yield loss, population development, detection probabilities of infestation foci by soil sampling, and calculation of cost/benefit of control measures and provides adequate advice for farmers to optimize financial returns. Farmers can compare cropping scenarios and ask "what if" questions. The DSS provides answers to the top 10 questions an extension officer is exposed to. A database with more than 500 potato cultivars is available with information on susceptibility for fungal and viral diseases, cultivar properties, and partial resistance, expressed as relative susceptibility, of the cultivar against both species of the potato cyst nematode.

NemaDecide is targeted to control potato cyst nematodes (*Globodera* spp.), *Pratylenchus penetrans*, and *Meloidogyne chitwoodi*. The latter two species have a broad range of hosts which necessitated the inclusion of a suitable number of crops to enable simulations of crop rotations over successive years. Almost 50 arable, green manure and vegetable crops, grasses, and some flower bulbs have been added. The system was extended with the population dynamics of *P. penetrans* and *M. chitwoodi*, both in the absence and presence of hosts. In addition, new population dynamic models and yield loss models had to be developed to include the competition between species when attacking the same host. NemaDecide has been developed in close cooperation with extension officers and was tested "on-farm" with more than 60 farmers. The system is connected to soil sampling companies to retrieve nematode sampling results.

2.4 Soil Herbicide Variable-Rate Application App

Christensen et al. (2009) describe site-specific weed control and variable-rate application (VRA) of herbicides as a way to reduce herbicide use in agriculture. The WUR developed and validated a regression model for VRA of soil herbicides

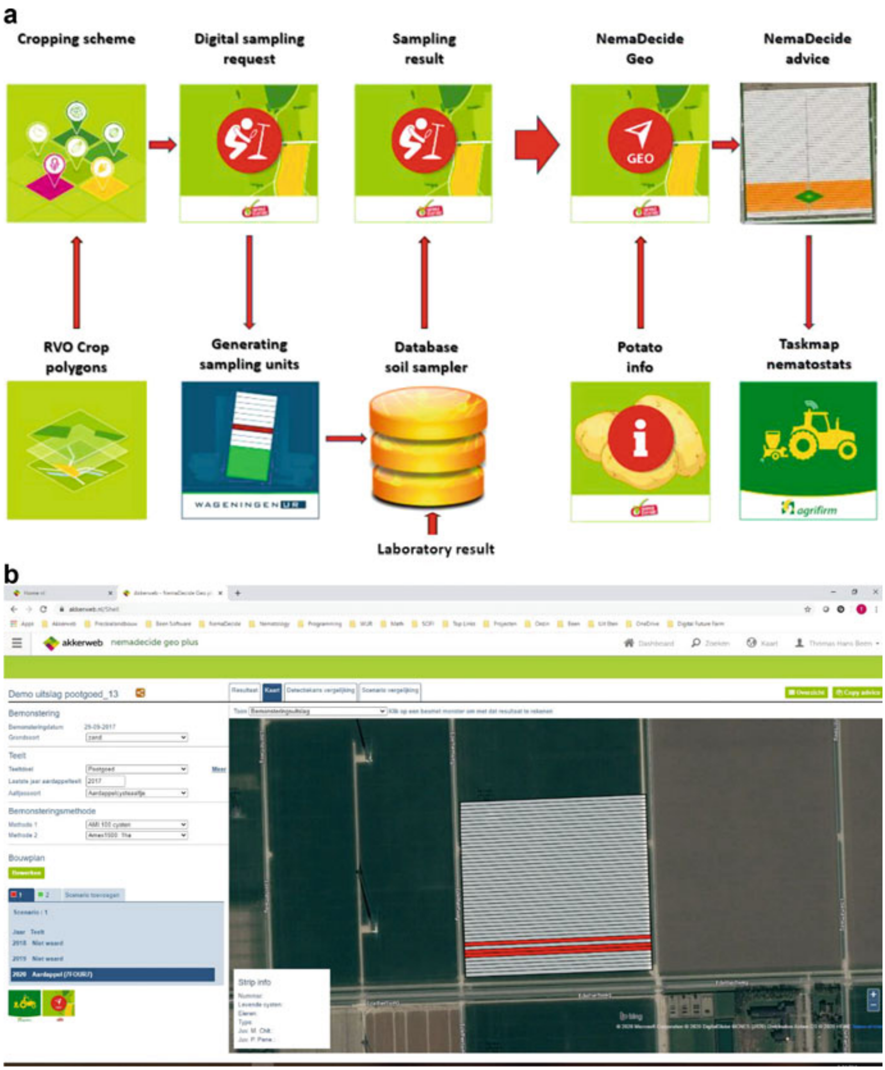


Fig. 4 (**a**) The NemaDecide digital chain. In the cropping scheme app, a farmer can download field boundaries from the government database. Selecting a field, the farmer can order a nematode sampling. The sampling agency uses the Stripbuilder app to generate the sampling units, and after collection and processing of the soil samples, the results will be returned to the farmer. He/she can now obtain advice from NemaDecide, choose the most suitable potato cultivar, or generate a task map for a granular nematostatic. (**b**) NemaDecide GEO application. On the right, a map of the parcel with the sampled strips and the detected infestation. To the left, the app dashboard

(SH) (Kempenaar et al., 2014a). The amount of soil herbicides used in a crop can be reduced by adjusting the dosage to site-specific soil conditions. Soil herbicides are more effective on parts of the field where soil organic matter and clay content are small. The application rate of soil herbicides can be decreased in those areas without

Fig. 5 Three steps in the soil herbicide apps. (**a**) Upload of soil organic matter map, (**b**) herbicide prescription map, and (**c**) machine-ready task map

affecting herbicide efficacy. The SH VRA model is integrated into a herbicide app on Akkerweb. The app requires a soil map that shows the variation of soil organic matter and/or clay of the field. The user of the app selects the dosing algorithm of the herbicide of interest to make a prescription map. The last step is to make the VRA task map set to the conditions of the user's sprayer. In Fig. 5, we show the steps from soil map to prescription map to task map. These steps also occur in the other VRA apps on Akkerweb. On-farm testing of this VRA soil herbicide system with sprayers that can vary the dose at a scale of ca 50 m^2 showed reductions in herbicide use of between 20 and 40%, with an average of 27% (Kempenaar et al., 2018). An additional benefit of site-specific optimization of soil herbicide use is less reduction in the growth of the crop, leading to increases in crop yield of up to 5%.

2.5 Variable-Rate Application App to Kill Potato Haulm

Modern potato farmers have to kill the aboveground green haulm of their crops before they can mechanically harvest the belowground potato tubers. Most commonly, they do this by spraying a nonsystemic defoliant or leaf desiccant herbicide some weeks before harvest (Kempenaar & Struik, 2008). Variable-rate application (VRA) of the herbicide is a way to minimize herbicide use in a rational way. The WUR developed and validated a regression model for VRA of potato haulm killing (PHK) herbicides (Kempenaar et al., 2014b). The more biomass present on a part of the field, as expressed in a crop reflection biomass index, the larger the dose of the defoliant should be. The PHK model is integrated in a potato haulm killing app on Akkerweb. The steps to make a PHK VRA map are similar to those for the SH VRA app. In this case, the app requires a biomass map that shows the variation in aboveground crop biomass (NDVI, WDVI, or other crop reflection index). The other steps to make the prescription and task maps are similar to those for the SH VRA app (see Sect. 3.4.3, Chap. 3). Figure 6 shows the data flow and output of the app. On-farm experiments with the PHK dosing model and app showed reductions in herbicide use of between 20 and 47%, with an average of 38% (Kempenaar et al., 2014b, 2018). The PHK model can also be used on variable-rate spraying on-the-go with sensors mounted on the sprayer and direct control of the dosing by the computer on the sprayer.

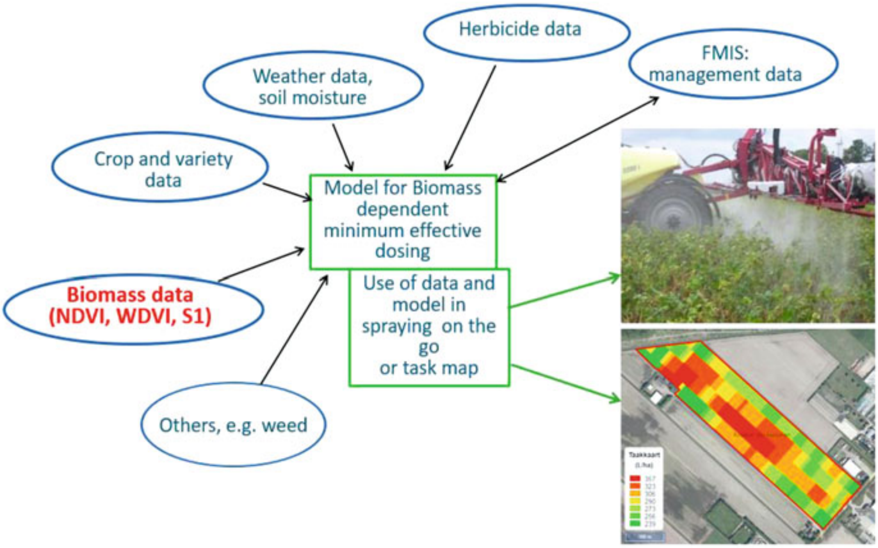


Fig. 6 Data input (blue text balloons) into PHK model (green text boxes) for biomass-dependent dosing and output of the model for direct control of the on-the-go sprayer or to a variable-rate prescription map that can be used to make a task map for a sprayer. For potato haulm killing, biomass data (in red) is the main driver in the model

2.6 Late Blight App

Potato late blight, caused by the oomycete *Phytophthora infestans*, is one of the most economically damaging diseases in potato. Annual losses are conservatively estimated at one billion euros for Europe and three billion euros globally (Haverkort et al., 2008). Current control methods rely primarily on frequent (calendar-based) fungicide applications (Cooke et al., 2011).

The Late Blight app helps farmers to optimize the timing of fungicide applications to prevent potato late blight. For this purpose, local measured and local forecasted weather data, obtained from the Akkerweb weather service, are analyzed to identify infection events in the near future and recent past (see Fig. 7a). Preventive fungicide applications are advised just prior to predicted infection events in the near future. Curative fungicide applications are advised to treat young, latent infections identified in the recent past. Eradicant fungicide applications aim to remedy older latent and active infections. The principles of the infection risk model in the app are described by Kessel et al. (2018).

The Late Blight app uses fungicide-specific ratings for rain intensity and protection of the foliage and tubers, for example, as published by Euroblight (www.euroblight.net), to calculate the time- and weather-dependent protection level of foliage and tubers. These ratings have been established through multiyear and

Fig. 7 (**a**) Data use and flow in the potato blight App: Forecasted and measured local weather data are used to calculate crop emergence, crop growth (LAI), pathogen infection events and (remaining) fungicide protection. Preventive fungicide applications are advised when an infection event is predicted in the near future AND the remaining fungicide protection is insufficient. (**b**) Screenshot of a Late Blight app advice on 28 May. On 30 May, an infection event is predicted by the infection risk model. That is why on 29 May, a preventive fungicide application is recommended (yellow). If this advice cannot be carried out, a curative advice (orange) or an eradicant advice (red) is issued for 30 and 31 May. The marker on 23 May indicates crop emergence. Spray advice is not issued before crop emergence

multicountry field trials and are updated when necessary. A further fungicide application is advised only when protection from the previous application is insufficient and an infection event is identified in the near future. The results are displayed in a simple interface which summarizes visually the key parameters and the advice (Fig. 7b). The Late Blight App operates at field level. It allows farmers to enter multiple fields. Advisors can view the results of multiple clients (farmers), each with multiple fields, once permission is granted by the client. The interface is built on a digital map of the farm or region with the potato fields highlighted in different colors representing the spray advice:

Green: No action is necessary
Yellow: A preventive fungicide application is advised
Orange: A curative fungicide application is advised
Red: An eradicant fungicide application is advised

In the next version, of the Late Blight app, the model is extended in a way that the resistance of the potato variety can be taken into account and variable-rate prescription maps can be made using crop biomass maps. This version has been tested in on-farm research since 2019.

2.7 Nitrogen Side Dress System (NSS) in Ware and Starch Potatoes

This application supports farmers to apply N side dress with variable-rate technology to maximize growth of the potatoes while minimizing the use of N (Booij et al., 2017, Booij and Uenk, 2004; Van Evert et al., 2012). In a side dress system, N is applied twice. Before planting, two-thirds of the nitrogen recommendation is applied as a flat rate by chemical and/or organic fertilizers (manure, compost, etc.). In late June or early July, a site-specific amount of side dress N is applied according to the crop's needs. To achieve this, canopy reflectance is measured with a satellite, an unmanned aerial vehicle (UAV), or a tractor-mounted sensor, and a vegetation index is derived. The application has the possibility to import a map of the vegetation index into the farmer's account on Akkerweb, or it can make use of already available data from other services on Akkerweb, like the Bioscope application, satellite application, or sensor data application.

The NSS app consists of three parts. First, the vegetation index map is converted to a nitrogen uptake map. Using relations derived from field research, a vegetation index like weighted difference vegetation index (WDVI) (Clevers, 1988) or chlorophyll index (CI) (Gitelson and Merzlyak, 1994; Gitelson et al., 2005), which give relative values, are converted to nitrogen uptake of the aboveground biomass of potatoes, which are absolute values in kg N per hectare. Second, an empirical growth curve is used to determine the amount of nitrogen that would have been taken up by a crop that is not limited by the availability of N. This curve takes into account the temperature sum between planting date and scouting date, expected yield, and the aim of the cultivation (ware or starch potatoes). Last, from the optimal and the measured nitrogen uptake, a site-specific recommendation is calculated (van Evert et al., 2012; Booij et al., 2017).

The nitrogen side dress system leads to an average reduction in the use of N of about 40 kg nitrogen per hectare with no reduction in yield (Van Evert et al., 2012) (Fig. 8 and Table 4). Additionally, in wet seasons, leaching of N is reduced (van Evert et al., 2017a, b).

Figure 9 shows the architecture of the NSS application. The user of the application must select a field within the crop rotation plan. These data are retrieved from the crop field app in Akkerweb. The variety and planting date are also included. Then, the user imports a biomass map, either manually from his/her own PC or from other applications on Akkerweb, such as the sensor data app, Bioscope app, or satellite app. The user must also fill in the expected yield. The application, in return, shows a nitrogen uptake map, the target nitrogen uptake derived from the optimum growth curve, and the recommended amount of side dress N. In the background, the

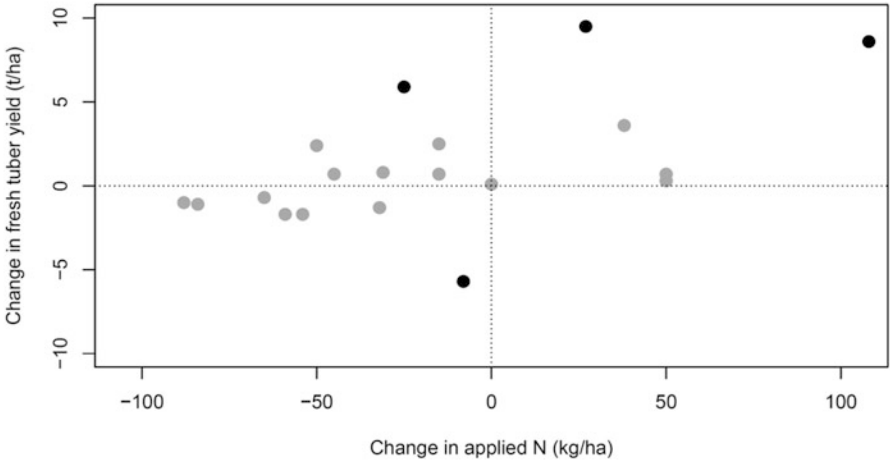


Fig. 8 Comparison of applied N and fresh tuber yield obtained with the recommended N rate and with the N side dress system. On the horizontal axis, the change in applied N with NSS relative to the recommended N rate is given. On the vertical axis, the change in fresh tuber yield is given. Each symbol represents an experiment. For black symbols, the yield difference was statistically different; for gray symbols, the yield difference was not statistically different. The overall trend is that if NSS recommends a large N rate, then yield is high, too, whereas if NSS recommends a small N rate, then yield is not affected

application connects to a webservice which contains the growth model and a connection to weather data. Last, the user can tune the recommendation by filling in the nitrogen content of the specific fertilizer that will be used, the minimum and maximum rate of N to be applied, and the grid size. A task map is then generated, which can be used in an up-to-date tractor terminal.

2.8 farmmaps Dashboard

The models and apps presented in Sects. 2.1 and 2.7 also run on the **farm**maps platform, the third version of Akkerweb, currently in development and available in spring 2021. **farm**maps features several improvements which resulted from observation on the interaction between farmers and Akkerweb and their needs observed during the last few years: data files are getting bigger and bigger, farmers like to be "taken by the hand," and everything should also be available on the mobile phone.

First of all, **farm**maps has an updated data repository which can process and store data independent of their size. Data can be dragged and dropped onto the map and analyzed to recognize the type of data and provide an image for visualization in one go. The properties of each file will be stored in a metafile for the rapid retrieval of files, appropriate for use in a certain application. Non-GEO data can be dropped on a

Table 4 Summary of tests with NSS

Year	Location	Soil	Cultivar	Use	N rate (kg ha^{-1})		Fresh yield (t ha^{-1})		Starch (t ha^{-1})		Sign.	Ref.
					Recomm.	Side dress	Recomm.	Side dress	Recomm.	Side dress		
2002	Colijnsplaat	Clay	Agria	Ware	80+54	80+0	62.5	60.8				1,2
2002	Colijnsplaat	Clay	Felsina	Ware	131+88	131+0	49.5	48.5				1,2
2003	Colijnsplaat	Clay	Agria	Ware	102+68	102+60	57.5	51.8			y	1,3
2003	Colijnsplaat	Clay	Felsina	Ware	141+94	141+35	44.9	43.2				1,3
2002	Rolde	Sand	Seresta	Starch	225	150+30	54.6	55.3	12.2	12.4		1,4
2002	Rolde	Sand	Mercator	Starch	155	120+20	53.2	53.9	11.3	11.5		1,4
2003	Rolde	Sand	Seresta	Starch	250	115+70	52.1	51.4	11.1	10.9		1,4
2003	Rolde	Sand	Mercator	Starch	185	90+70	49.3	55.2	9.9	11.4	y	1,4
2010	Valthermond	Sand	Seresta	Starch	225	175+100	47.8	48.5	10.0	10.2		5
2010	Colijnsplaat	Clay	Victoria	Ware	250	150+50	44.4	46.8				5
2011	Valthermond	Sand	Seresta	Starch	120+60	120+45	46.6	49.1	10.3	10.5		6
2011	Reusel	Sand	Fontane	Ware	165	219+54	78.6	87.2			y	6
2011	Reusel	Sand	Fontane	Ware	229	229+27	91.4	100.9			y	6
2011	Biddinghuizen	Clay	Milva	Ware	150+54	150+54	70.9	71.0				6
2012	Vredepeel	Sand	Fontane	Ware	266	145+90	78.0	78.8				7
2012	Hulsberg	Löss	Fontane	Ware	182	150+0	63.5	62.2				7
2013	Vredepeel	Sand	Fontane	Ware	287	150+53	70.6	69.5				7
2013	Hulsberg	Löss	Fontane	Ware	171	150+59	58.3	61.9				7
2014	Valthermond	Sand	Seresta	Starch	205	205+50	49.6	49.9	10.9	10.7		8

The difference between yields in an experiment is statistically significant if a “y” is noted in column “Sign.” Reports cited are [1]Van Evert et al. (2012), [2]Slabbekoorn (2002), [3]Slabbekoorn (2003), [4]Van Geel et al. (2004), [5]Van Evert et al. (2011), [6]Van der Schans (2012), [7]Van Geel et al. (2014), [8]and Van Geel and Van der Schans (2015)

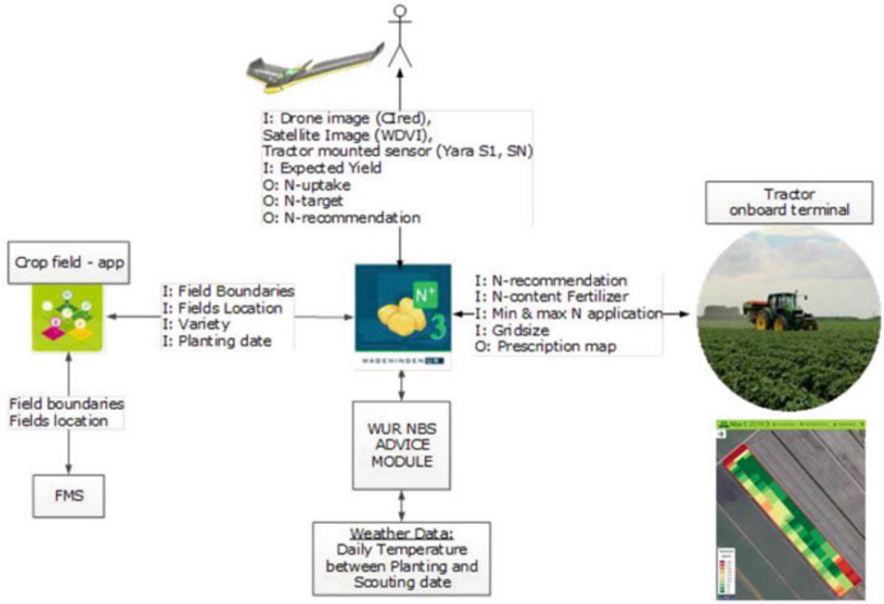


Fig. 9 Schematic flow of inputs (I) and (O) in Akkerweb NSS app. A task map based on CI map and NSS model and expected yield of 55 tons per ha is shown

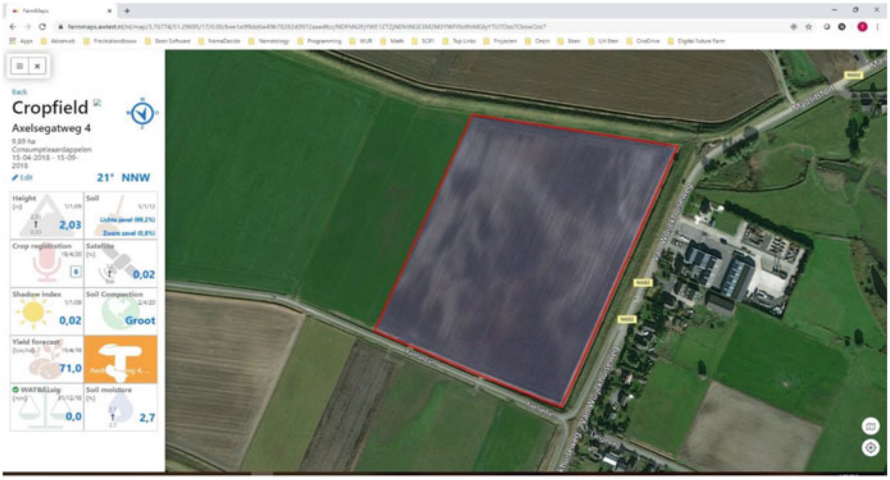
parcel and will be georeferenced and are viewable (Excel, Word, PDF, images). The farmer can now store and retrieve all information concerning his parcel.

The concept of "workers" is introduced, small pieces of code that carry out automatic and, if necessary, scheduled tasks that can also be triggered by events and which fuel the dashboard by constantly updating the information presented.

The interface is created in Angular which means that **farm**maps can run on all devices, including mobile phones. The most important interface change is the use of information widgets in a dashboard (Fig. 10a) that is eventually intended to provide the farmer with an instant overview concerning the current state of his farm, including the necessary alerts to take action if required. The widgets present condensed information and alerts. More specific information can be obtained when opening the widget (Fig. 10b). Clicking on the icon will take the user to the app that will solve the problem. This three-tier approach should provide a more intuitive approach for a farmer than a selection of 30+ different single app tiles on a dashboard.

The models running on Akkerweb are also available on **farm**maps. However, the new engines are implemented as web services that will be available to third parties who like to use these engines but prefer to use and present them on their own GEO-platform with their own interfaces.

(a)



(b)

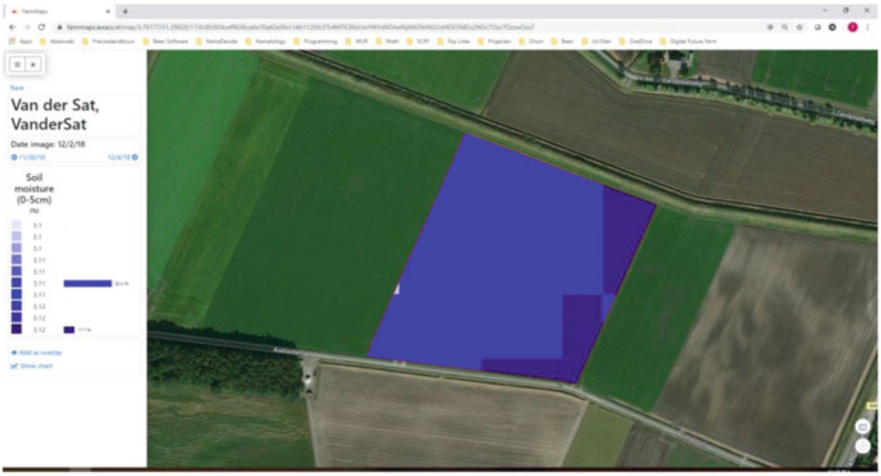


Fig. 10 farmmaps look and feel. (**a**) Dashboard with widgets giving soil and crop information. Detailed information can be provided by opening widgets. (**b**) Soil moisture data as measured with radar remote sensing. Widget information on water availability and deficiency is shown in Fig. 2 on the crop growth of potato in Fig. 3

3 Outlook

It is likely that precision agriculture will become more mainstream in the coming years contributing to more sustainable and circular crop production and that farming and value chain optimization will be based on data to a much greater extent. This transition will be much influenced by the availability of service platforms like Akkerweb that bring together all relevant data in a safe farm data space where the farmer has control over his data. He wants to use the data to monitor and benchmark his crops, to report to chain partners, and to make better management decisions. In addition, digital agri-food chains can be optimized, and tracking and tracing become possible when we have mature value chains. The question is when will this all become mainstream, for example, more than 50% of the farms in countries like the Netherlands use data to do all aforementioned farming activities. A few issues still have to be solved to reach this stage (today, we estimate that less than 1% of the farms in the Netherlands are mature data-driven farms). Farmers must become convinced that data-driven farming is not too complex, that the investments bring significant added value, and that data will not be misused. Ease of use, equal sharing of benefits across the value chain, and trust by good governance will be crucial in making data-driven farming mainstream.

Conflict of Interest The authors declare that they are employed by the Wageningen University & Research, which is the sole member of the not-for-profit foundation that owns and exploits Akkerweb and **farm**maps.

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