IPM Decisions

D4.15 DSS evaluated for economic and environmental benefits: weeds

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1 Public Summary

Two DSS for weed management were evaluated. The first, IPMWise, takes a more tactical view and considers within season control. The second, Weed Manager, guides management over the rotation. Our analysis shows that these approaches can provide robust effective control.

2 Executive Summary

We evaluate two DSS for weed management. The first, IPMwise, is a commercial product with significant uptake in the farming community and provides a framework for optimizing weed control interventions (both chemical and non-chemical) tailored to specific management and environmental contexts, takes a tactical view and considers within season control. The second, Weed Manager, optimises the system scale management context (cultivation, rotation, and input intensity) which determines the relative impact of a change in herbicide strategy. This system is not implemented commercially but has mainly been used for knowledge transfer and generating scenarios

The work of customizing IPMwise for a new country, is a comprehensive task. Until now, such work has been undertaken by universities, and in Denmark and Spain by spin-out SME companies. To reduce the costs of customization, and where appropriate, efficacy data is shared between countries. For example, in the 2000s, the IPMwise and predecessors were customized for conditions in Norway, where Danish efficacy data were included for interpretation and merging with Norwegian efficacy data, to fill in specific data gaps. After some iterations of design, construction and field tests, this method led to an agronomically robust and economic/-environmental sound version of IPMwise for Norway. Later, this method was used also in Germany and Spain. In these 4 countries, a total of 46 arable crops have been included, and full assortments of herbicides and weed species. In Greece, the first prototype in wheat is currently being validated, as part of the IPM Decisions project, WP4.

Implementation in practice of Directive 2009/128/EC, Annex III, which defines 8 IPM principles, may represent a step change in the prospects for weed decision support systems, if public access can be provided to 'EU-registration reports, Part 7', which contain summaries efficacy data on pesticide products. Such access has already been provided in Denmark for years, and such data constitute the 'backbone' of IPMwise. Such public access will benefit farmers, crop advisors, suppliers of DSS, the environment and additional stakeholders. IPMwise specifically addresses 7 of the 8 IPM principles.

When compared to national/local 'best practice treatments' in the 5 countries, and across 46 crops, with full assortments of herbicides and weed species, 27-40% reduction of herbicide use (measured as cost, treatment frequency index TFI and similar), has been achieved in plot trials.

Despite this potential, the requirement for manual field inspections has been identified as a major obstacle. Accordingly, 'RoboWeedMaps' technology was developed in Denmark, where currently 84 fields have been systematically photographed. Weed infestations were determined by use of 'machine learning' (ML) and 'virtual field inspections' of pictures as supplement. This delivered connected data on weeds species, growth stages and densities in each field. When using the farmer's planned/executed herbicide treatments as reference, and IPMwise for minimization of treatments, 57-73% reduction of herbicide cost was found in different winter cereals. However, additional development of ML, and additional field validation is required to furtherly document both agronomic robustness and economic/environmental potentials of this technology.

These results indicate that the decision algorithms and equations included in IPMwise have generic qualities, which are suitable for scaling both up (to additional crops) and out (to additional countries), also with considerable economic and environmental potential. However, the requirement of manual field inspections as input, has been identified as a major barrier for a wider implementation of IPMwise. Image analysis methods offer a potential solution to this barrier. Elements on pictures, which can now be auto discriminated by machine learning algorithms. However, before these methods can deliver spray maps for site-specific treatment in large scale, additional ML-training is required on the weed species level.

The rotational view of Weed Manager was developed in the UK in the early 2000s. The systems consider the response of the weed seedbank to crop choice, sowing time, herbicide kill and tillage. Underlying the system is a basic life cycle model. It is viewed as a tool for farmers to explore and understand how management can impact long-term weed population dynamics. At the time of its development weed manager was validated by a limited data set and expert opinion. Here we further validate the system with data from France and show that just over 75% of the time the broad pattern of weed population dynamics are accurately captured.

The different stage of development of the two systems is reflected in the maturity of the validation work and quality of the evidence for evaluating their potential economic and environmental benefits. IPMwise now has a strong evidence base, compiled from multiple countries on herbicide efficacy and outcomes of contrasting strategies, that means reductions in herbicide use (of up to 40%) suggested by the system can be implemented with confidence without compromising productivity or economic returns. Weed manager remains a useful tool for exploring alternative scenarios of cropping system design that could have an impact on the potential for realizing these potential reductions.

3 Introduction

Weeds represent a serious threat to crop production worldwide (Oerke and Dehne, 2004). In agricultural production, weeds can occur as wild plants that establish within the agricultural landscape or as volunteers from previous crops. Herbicides are used extensively to control weeds in crop production systems. However, the use of herbicides has negative impacts on the environment. Plant protection products (PPPs) can contaminate surface water, ground water and the atmosphere (Blanchoud *et al.*, 2002; Annett, Habibi and Hontela, 2014) leading to biodiversity losses, loss of ecosystem function and other problems for humans such as contamination of drinking water. As a result, there are an increasing number of regulations being placed on herbicides, reducing their usage. Another issue is that resistance is emerging to some key herbicide products rendering them ineffective and also putting additional pressures on farmers and advisors to think carefully about how to deploy herbicide products.

Herbicides are often used tactically rather than strategically, that is to say the choice of product and dose is driven by the situation in the current season with less thought given to the potential to regulate weed populations through strategic choices of crop sequences and targeted tillage that will determine the potential to reduce within year herbicide use. The decreasing number of chemical products available to farmers, the risks of resistance evolution and the increasing pressures to reduce pesticide use around environmental concerns has put a growing emphasis on taking a strategic approach to weed management through integrated weed management (IWM) (Neri *et al.*, 2011; Hahn, 2014). The key tools for IWM include inversion tillage, diversifying crop rotations, adjusting sowing times and more precise use of herbicides (Harker, 2013). Designing effective IWN programmes is a complex task and requires an in-depth understanding of the dynamics of weed populations (Fernandez-Quintanilla, 1988) as many cultural control methods focussing on the species' biology and ecology are often incorporated into such programmes.

Decision support tools have a key role to play, offering farmers advise on where herbicide doses could be reduced and allowing them to explore the possible implications and trade-offs of an IPM approach. This deliverable focuses on evaluating weed decision support systems (DSS). For this we consider two DSS the Danish IPMwise tool which takes an in-season tactical approach to decision making and adresses also long-term aspects by ensuring low residual weed infestations, and the Weed Managament Support System, which takes a more strategic longer-term view (being a useful tool for exploring alternative sceanrios for knowledge exchange and generating hypotheses) .

3.1 IPMwise

In Denmark, the design, construction, and field validation of DSS for IWM has been ongoing since 1989. This 32 years of DSS research in Denmark was structured and supported economically by a series of Danish Political Action Plans. Initially, these plans aimed to reduce pesticide use by 50%, in terms of both the total amount of active substances used and the TFI. In the 2000s, and as an additional incentive, taxation on pesticide products was introduced. The newest DSS for IWM, known as IPMwise, was designed, constructed, and delivered by IPM Consult in 2016.

Currently, two IT/agronomic generations of this tool are commercially available in Denmark:

- A 3rd generation predecessor tool, 'Crop Protection Online – weeds', which was released in 2003 by the Danish Advisory Service SEGES in collaboration with Aarhus University, department of AgroEcology.
- A 4th generation tool, 'IPMwise', which was released in 2016 by IPM Consult and distributed by Datalogisk, which also provide a Farm Management System called 'Naesgaard Mark'. IPMwise includes unique features for: herbicide resistance management, options for recommendation of specific methods for mechanical control, treatment maps for site-specific weed control and other functions.

Besides construction and validation of DSS, the political action plans also included:

- Re-evaluation of all registered pesticide products, with the aim of protecting Danish groundwater resources
- Identification and quantification of major factors affecting pesticide efficacy, by systematic testing all important pesticides in dose rates ranging from 1/16 to 1/1 of registered pesticide dose rates. Both field- and semi-field experiments were used for these tests. Together with data from 'EU registration reports, Part 7', these data on herbicides, constitute the 'backbone' of both IPMwise and predecessors
- Support to advisory services and additional activities.

In the early 1990s, the first attempt of 'system export' of Danish predecessor DSS for IWM was made. The fully field validated Danish DSS was used to find herbicide treatments against weeds in Dutch maize fields. The results from these field tests were clear in terms of too many plots with both severe yield loss and unacceptable residual weed infestations (Van der Weide, 1995).

In the 2000s, international collaboration projects were initiated to expand the use of the Danish DSS for IWM across Europe. However, instead of re-using Danish estimates for parameters included in algorithms and dose-response functions, country specific parameterization was used. In cases where there were identical herbicide products and weed species in geographically close countries, efficacy data were exchanged for use in national interpretation and estimation. This method of exchange is still practiced between Denmark and Norway for mutual benefit, and with no cases of unsatisfactory results from field validation experiments.

In the EU project ENDURE (2007–2010), 70 Decision Support Systems (DSS) for Integrated Pest Managed (IPM) were analyzed, and 'best parts' in terms of reducing dependency and use of pesticides were identified (Been et al., 2009). For IWM, 9 DSS were analyzed, of which 'best parts' in terms of reducing dependency and use of herbicides, were identified in 3 DSS, originating from France, Italy and Denmark, respectively. The DSS from Denmark was found notable in terms of economic/environmental potential and level of uptake.

3.2 Weed Manager

Weed Manager was a collaborative Sustainable Arable LINK (LK0916) project between ADAS, Rothamsted Research, Silsoe Research Institute and SAC (now SRUC) that ran for 5 years from October 2000. The aim of this project was to develop and validate 'Weed Manager', a Decision Support System module designed to provide farmers, agronomists and distributors with a robust tool to plan and develop weed management strategies. The system consists of a 'within-season' planning tool to investigate a range of weed management strategies in a winter wheat crop in a single season, and a 'rotational' planning tool allowing users to consider weed control options over a six-year arable cropping period. It is the latter tool we evaluate here.

The rotational model of Weed Manager aimed to predict the impact of rotation, sowing time, cultivation type and herbicide application on a given weed population. The rotational view of Weed Manager was designed to provide information and guidance on strategic management of weed populations over several years in a crop rotation. Weed Manager contains full sets of parameters for the major UK arable weeds (e.g. black-grass, wild-oats, cleavers chickweed), but the current version only includes a total of 12 species. Herbicide-resistant and susceptible biotypes of grass and broad-leaved weeds are treated separately. The user can propose a range of cultural practices, rotations and weed control options and the system will calculate the yield losses and economic consequences for a single season or through a rotation. Alternatively, they can use the decision part of the system. Using a biological model of seedbank dynamics it optimises the choice of sowing date, type of cultivation and herbicide cost to find the best weed management strategy throughout a defined rotation of up to 10 years. The rotational model was validated by the expert opinion of weed agronomists in the project team and the limited data sets that were available at the time (see Benjamin et al., 2009).

In this report we describe the functionality of the two systems. In the case of IPMWise, which has been evaluated extensively across Europe and most recently in Greece, we review the experimental studies that have been conducted across five countries and so collate evidence of the value of using this DSS for farmers. In the case of Weed Manager we evaluate the model against data that were not available at the time of its development to explore its more general applicability across crops and environments. For both we contextualise this research in terms of the principals of IPM and draw some generic conclusions.

4 Method

4.1 The IPMwise DSS

4.1.1 Description of the IPMwise toolbox functionality

The toolbox available to all IPMwise-countries includes:

- 'Consultation', which based on a field report on weed infestation will quantify needs for weed control and find connected optimized options for control (minimized for cost, TFI or ELI)
- 'Users own herbicides', which will restrict 'Consultation' to search for options for control, among herbicides on this list (which may be already in the farmer's storage)
- 'Profile', which present the expected efficacy of the user's selection of: 1 herbicide product on combinations of standard dose rates, weed species and classes of weed growth stages, temperatures and drought stress.
- 'Mixture', which present the expected efficacy of the user's selection of 2-4 way herbicide tank-mixtures
- 'Overview' which present the expected efficacy of all herbicides available in the user's selection of crop and season (spring / autumn in countries, which have strong winter)
- 'Herbicide mode-of-action' (MOA), which present an overview herbicide product names and content of herbicide MOA, which is important to farmer's to protect against new herbicide resistance

IPMwise also includes facilities to manage different technology readiness levels (TRLs). These facilities can manage:

- prototype versions, to be used only by constructors for field validation experiments
- pre-release versions, to be used only by constructors for functional test after new updating
- officially released versions, accessible to end-users.

A login system ensures that persons who have different roles can access different versions.

4.1.2 Methods for construction and validation

A general challenge in weed management in Europe is that most measures for control need to be applied relatively early in a growing season, while farmers wish to ensure proper levels of weed control until harvest time. To farmers and crop advisors, the main criteria for evaluating the success of measures for weed control will often be:

- Securing of yield potential
- No/low propagation of weeds

In predecessor DSS versions, this was examined by design and construction 2-3 prototype versions, which included a gradient of 'need for control' managed by a sub-model, which included combinations of:

- Threshold value of weed density, below which no herbicide is applied
- When the threshold value has been exceeded: increasing values of efficacy targets according to target efficacy and -how efficacy is expected to be vary with weed growth stage. greatest.

Over the years, this sub-model has been developed for combinations of crop, season (autumn or spring), weed species and weed density. In each case, upon completion of a set of field validation trials, the need for adjustments was evaluated, and new validation trials were executed as required. Such iterations are intended to identify suitable balances between farmers' requirements and the lowest possible input of herbicides. In many countries and crops, a total residual weed infestation of up to 10–15% ground cover of weeds at harvest time, are considered acceptable (Rydahl, 2004). However, many exceptions exist of lower tolerance, for example when producing seeding lots, certain crops for human consumption, etc.

Considering parameterization of dose-response functions, the work started with designs, which focused mainly on 'low-hanging fruits' in terms of expected economic and environmental potential. Such initial designs included differentiation in herbicide application according to combinations of crops, weed species and classes of weed density and weed size. Later, additional variables were integrated. These were: influence of temperatures, relative humidity, drought stress and synergistic/antagonistic effects of herbicide tank-mixtures.

Since 1989 more than 2000 field validation trials have been executed in Denmark to test prototypes of DSS for IWM, with more crops and still more advanced designs. In this work, an iterative process was designed and used. Upon 2 years of satisfactory field tests (no yield loss and max. 10–15% total weed cover at harvest time) in still more crops, official versions were released for use in Denmark.

4.1.3 Methods for agronomic and legal customization of IPMwise for national conditions

IPMwise is an online system consisting of one version of a generic code, which does not contain specific agronomic, legal, or lingual content. All such information is stored in an integrated database-schema, where each participating country has its own database version. Such database editors are referred to as 'national managers of IPMwise'. The database may be perceived as a 'dash-board', in terms of switching on/off different agronomic and lingual features. Some of these can be switched on/off on the global level, while others can be switched on/off the crop level. In this way both agronomically simple and advanced setups can be managed on the national- and crop levels. A technical manual supports all options for editing.

In terms of data for estimating dose-response parameters, the 'backbone' is efficacy data on varying weed species, weed growth stages, temperatures, etc. Accessibility to such data and additional information differs between countries. In some countries, EU registration reports for pesticide products, where Part 7 contains summarized efficacy data, are publicly available. In other countries, access to efficacy data has been achieved from agrochemical companies, where in some countries, universities function as connecting partners.

Across countries currently working with IPMwise, data and additional information on efficacy will usually be abundant in major crops, while in minor crops, only relatively sparse amounts of data and information will be available. In some cases, only information from herbicide product labels, will be available. IPMwise has been designed to transform and interpret almost whatever information is available into:

- estimates of parameters for calculation of values of 'efficacy targets' and
- estimates of parameters in a dose-response function, which provide continuous relation between herbicide dose rates and relative efficacy on a weed species level (plus optional classes of weed growth stages, temperatures, and drought stress)

This data needs to be updated, when new herbicide products are launched, when new efficacy data becomes available and when existing products disappear. Also changes in legal conditions, which are getting still more complex in several EU-countries. Some legal aspects are subjected to 'EU-crop compliance', which may affect economic subsidies to farmers, and must therefore be updated regularly. In case of just a few bad recommendations by DSS, risks of 'sudden death' of such DSS have been reported (Been et al., 2009).

IPMwise may be perceived as a method to systematically collect, interpretate and present continuously changing data and information. Upon customization for major crops, and with full assortments of herbicides and weeds, IPMwise is likely to find over 50 options for control of common weed infestations. In minor crops, however, IPMwise may only find few options for control and only for relatively simple weed infestations. However, these conditions will probably be the same, irrespectively of using IPMwise or alternative methods for decision support.

4.1.4 Status on customization of IPMwise in different countries

4.1.4.1 Status on customization and organizing in Denmark

On requests by IPM Consult, the Danish Environmental Protection Agency (Danish EPA), supplied summarized efficacy data on herbicides, in terms of 1) 'EU registration Reports, Part 7', and 2) other report formats, which had been used for older herbicide products. In addition, reports from projects executed by Aarhus University, AGRO, in context of Danish Pesticide Action Plans to identify and quantify factors of affecting herbicide efficacy, were widely used.

The first official version of IPMwise was released in 2016. The current version includes:

- 32 crops, plus relevant 'undersown crops',
- 120 weeds, hereof 15 already herbicide resistant biotypes,
- 104 herbicide products, inclusive generic products
- 18 adjuvant products, inclusive generics
- 374 herbicides tank-mixtures (2-4 way)
- 2 methods for mechanical control
- 20,787 estimates of dose-response parameter for combinations of crop, season, herbicide/mechanical control and weed species
- 2 herbicide mode-of-action (MOAs) (ACCase and ALS) for anti-resistance management

IPMwise and predecessor systems are recognized by Danish advisors and crop protection companies as a professional point of reference.

IPMwise has been technically integrated with the Danish Farm Management System (FMS), named 'Naesgaard Mark', which is provided by Datalogisk A/S. Datalogisk also sell annual subscriptions to IPMwise.

4.1.4.2 Status on customization and organizing in Norway

The first official Norwegian version of IPMwise was released in 2003. The current version includes:

- 4 crops (cereals), plus relevant 'undersown crops'
- 49 weeds, incl. 7 already herbicide resistant biotypes
- 41 herbicide products, incl. generics
- 5 adjuvant products, incl. generics
- 267 herbicides tank-mixtures (2-way)

- 2,937 estimates of dose-response parameter for combinations of crop, season, herbicide and weed species
- 1 MOA (ALS) for prevention/delay of new herbicide resistance

The Norwegian version IPMwise is named 'VIPS-Ugras 2.0', and the agronomic content is managed by NIBIO in the University of Ås, assisted by IPM Consult.

The Norwegian State pays annual cost according to contracts between NIBIO and IPM Consult.

'VIPS-Ugras 2.0' is recognized by Norwegian advisors and crop protection companies as a professional point of reference.

4.1.4.3 Status on customization and organizing in Germany

The first official release of IPMwise is planned for February 2022. This version will include:

- 3 crops (winter barley, winter wheat and maize)
- 87 weeds, incl. 16 already herbicide resistant biotypes
- 144 herbicide products, incl. generics
- 14 adjuvant products, incl. generics
- 554 herbicides tank-mixtures (2-way)
- 2,913 estimates of dose-response parameter for combinations of crop, season, single herbicides and weed species
- 2 methods for mechanical control

Field validation experiments in crops were finalized in 2021.

The Germany company ISIP, who already supply various online tools for IPM of some fungal diseases and insect pests, will include also IPMwise, where access can be obtained by annual license payments.

Field validation trials have been widely supported voluntarily by German crop advisor companies, which in this way demonstrate their support to the concept.

4.1.4.4 Status on customization and organizing in Spain

The first official release was made in 2019. The current version includes:

- 19 crops (spring- and winter cereals, maize, oilseed rape, soja, lupine, chickpeas, lentil, green pea, almorta, beans, sunflower)
- 175 weeds, incl. 22 already herbicide resistant biotypes
- 182 herbicide products, incl. generics
- 11 adjuvant products, incl. generics
- 1,772 herbicides tank-mixtures (2-3 way)
- 21,005 estimates of dose-response calculations for combinations of crop, season, single herbicides and weed species
- 2 methods for mechanical control

- 4 MOAs (ACCase, ALS, Auxin and Metabolic) for anti-resistance management

A spin-out company named 'IPM Advise' was registered on 29th November 2021. This company is owned jointly by Spanish 5 partners, whom are related to University of Lleida (UdL).

IPM Advise will sell annual licenses to the Spanish version of IPMwise in collaboration with the Spanish company AgroSLab, who provides online Farm Management System (FMS) and IPM Consult.

4.1.4.5 Status on customization and organizing in Greece

A prototype version has developed in context of the IPM Decisions project, WP4 (see D4.7). This version currently includes:

- 1 crop (wheat)
- 13 weeds
- 5 herbicide products
- 2 adjuvant products
- 14 herbicide tank-mixtures
- 123 estimates of dose-response calculations for combinations of crop, season, single herbicides and weed species

Beside that a PhD study executed by Alexandros Tataridas in Agricultural University of Athens (AUA) has been set up, which includes field validation experiments in Greek fields.

4.2 Weed Manager

4.2.1 Description of the Weed Manager functionality

The Weed Manager uses stochastic dynamic programming (SDP) to find the management program that maximises the economic value returned from a specified crop rotation (Benjamin et al., 2009; Tatnell et al., 2006). Specifically, given a crop rotation, Weed Manager estimates the recommended cultivation method (ploughing or non-inversion, or for potatoes rotation), sowing date of the crop (early, mid, or late) and intensity of herbicide program (low, medium, high, very high) to maximise the return over a number of years.

4.2.2 Stochastic Dynamic Programming framework

The SDP algorithm requires that the state variable is discrete, and that there are a finite set of actions that can be taken. In Weed Manager the state variable is the binned density of seeds within the seed bank in two layers of the soil (shallow, those above 5cm, and deep, those between 5cm and 25cm), and so $x \in X$, denotes the density band of each layer of soil at the start of a growing season (for example, x might refer to between 50 and 100 seeds per m^2 in the shallow layer and between 10 and 20 seeds per m^2 in the deep layer). Each action,

$k_t \in K$, in Weed Manager is some combination of cultivation (inversion ploughing or non-inversion), herbicide program intensity (from low to very high), and sowing time (either early, mid or late).

Having defined the state variables and the potential actions, the following arrays are defined:

- The "value" of taking a particular action, k, when in a particular state, x_i, which we term V_i^k. In Weed Manager, this value is the income generated from the crop (incorporating yield loss by the weeds), minus the costs of carrying out the given management program.
- The probability of moving from state x_j to state x_j in the following year, given that action k was applied: p_{ij}^k.

Both of these variables are calculated using the biological model, described below.

Finally, the SDP algorithm calculates the optimal expected financial reward for each state x_i in year t onwards, $f_t(i)$. The SDP algorithm works backwards in time, starting from the final year of the simulation, using the following recursive equation:

$$f_t(i) = \max_{\mathrm{k}} \left\{ \sum_{j=0}^{N} \left[V_i^k + \lambda p_{ij}^k f_{t+1}(j) \right] \right\}$$

In short, the optimal expected financial reward for state x_i is produced by the set of management actions, k, which produce the greatest financial return from that time onwards. For a given action, k, the value from time t onwards is made up of two components: firstly, the value attained in that year by applying action k, V_i^k; and secondly, the probability of being in each subsequent state, x_j, multiplied by the optimal expected financial reward in that state in time $t+1$ onwards, multiplied by a discount, λ, to reduce the significance of more distant years.

4.2.3 Biological model

As mentioned above, to define the value attained when performing action k on a system in state x_i, V_i^k, and the probability of moving from state x_i to state x_j given action k, p_{ij}^k, Weed Manager uses a within-season biological model derived from Moss (1990), which we describe briefly here. Comprehensive details can be found in Benjamin et al., (2009).

Denote the density of weed seeds in the shallow and deep soil layers as $N_s(t)$ and $N_d(t)$ respectively. When soil is cultivated a proportion of seed is moved between the soil layers, with u the proportion moved up from the deep soil layer to the shallow soil layer, and d the proportion that is moved from the shallow soil layer to the deep soil layer. A proportion, g, of the seeds in the shallow soil layer germinate and become seedlings and then mature plants.

The three management practices affect the density of mature weed plants. Cultivation, whether inversion or non-inversion, results in all emerged seedlings up to that point being killed. The proportion of seeds that have emerged that are killed at cultivation, θ, is defined by the sowing date, with later sowing dates killing a larger proportion of weeds. To calculate θ, three dates were described for each crop, specifying an early, mid, and late sowing date, and an emergence curve was parameterized for each weed species, $E(t) = \epsilon_1 t^3 + \epsilon_2 t^2 + \epsilon_3 t$, where $E(t)$ is the rate of weed seed emergence. The proportion of seeds that have emerged at sowing, θ, is the proportion of the emergence curve that would have emerged by the sowing date, $\theta = \frac{\int_0^D E(t)dt}{\int_0^{EOS} E(t)dt}$, where $t = 0$ denotes the start of the growing season, D the sowing date, and EOS the latest time that weed seeds could emerge and produce seeds in that growing season. The herbicide program kills some proportion of the mature weed plants, h. To discretize the herbicide program, four levels of program intensity were defined for each weed species (low, medium, high, and very high), and the mortality of each weed was specified for each given herbicide program intensity.

The density of mature weed plants in season t, $N_m(t)$, is therefore:

$$N_m(t) = (N_s(t)(1 - g\theta)(1 - d) + N_d(t)u)g(1 - h)$$

The density of seeds in the seed bank at the start of the next season depends on the number of viable seeds that fall back on the shallow soil layer, $S(t)$, and the proportion of ungerminated seeds that die in the soil each season, m.

The density of viable seeds is:

$$S(t) = \frac{N_m(t)(1 - n)\nu\beta}{1 + \alpha N_m(t)}$$

where β is the number of seeds per plant, n the proportion of seeds lost to natural causes, ν the proportion of seeds that are viable, and α is the reciprocal of the plant density.

Finally, the density of seeds in the next season is the density of new seeds in addition to those that survive from the year before:

$$N_s(t + 1) = S(t) + (N_s(t)(1 - d)(1 - g\theta) + N_d(t)u)(1 - g)(1 - m)$$
$$N_d(t + 1) = (N_s(t)d(1 - g\theta) + N_d(t)(1 - u))(1 - m)$$

4.2.4 Defining p_{ij}^k and V_i^k

To estimate p_{ij}^k, the density of seeds in the following growing season is calculated at each of the density band limits. That is, given a density band from u_1 to u_2 in the shallow soil layer, and from d_1 to d_2 in the deep soil layer, the four combinations of each (u_1, d_1), (u_1, d_2), (u_2, d_1), and (u_2, d_2), are used as the starting seed bank densities, resulting in four estimates of $N_s(t+1)$ and $N_d(t+1)$. The maximum and minimum of these estimates specifies a new seed density range in each soil layer, and the probability of moving from state x_i to x_j is defined by the proportion of this new range that overlaps each defined density band.

The value, V_i^k, is the economic return in a year starting in state, x_i, with management program k, incorporating both the realized yield from the crop (minus the weed-induced yield loss), as well as the cost of the management program.

$$V_i^k = \left(Y_k - L_i^k\right)M - V - C_k$$

where Y_k is the yield loss when unaffected by weeds with action k, such that $Y_k = Y_0\phi$, with ϕ the proportional reduction in potential yield due to the given sowing date, L_i^k is the yield loss due to the weed pressure and management programs, M is the value of the crop, V is the sum of other variable costs, C_k is the monetary cost of the chosen management program, where $C_k = C_H + C_C$, the sum of the cost of the herbicide application program, C_H, and the cultivation program, C_C. All these parameters are specific to the crop/weed in question and have been parameterized from the literature or expert opinion.

It only remains to define amount of yield lost to the weed density, which is given by the following:

$$L_i^k = \frac{Y_k r N_m(t)}{1 + \gamma N_m(t)}$$

where r and γ are species specific constants, giving a maximum yield loss of $\frac{Y_k r}{\gamma}$.

Horizon 2020

4.2.5 Data

Data was kindly provided from the authors of Yvoz et al., (2020), a study of how different management strategies affect weed communities. The data consist of estimates of the seed density of 7 weed species (*Alopecurus myosuroides*, *Avena fatua*, *Chenopodium album*, *Galium aparine*, *Lolium spp.*, *Papaver rhoeas*, and *Polygonum aviculare*, all already included in Weed Manager), binned into different density classes, derived from field cores (Figure 1). Data from 7 rotations were provided with crops including spring barley, winter barley, spring oilseed rape, winter oilseed rape, winter wheat, winter mustard and sunflower, each rotation covering 6 years, together with the performed management information was provided, as described in Table 1 of Yvoz et al., (2020). As neither winter mustard or sunflower were included in Weed Manager, winter oilseed rape and spring oilseed rape parameters were used to parameterize the crops respectively, being crops with similar planting dates and competitiveness. Expected yields and prices were found for each crop.

Whether the field was ploughed each year was a reported variable, and so corresponds to inversion or non-inversion cultivation in Weed Manager. Herbicide intensity was derived from Ratio_TFI_Herbi, a crop-specific normalized variable, indicating the number of full herbicide doses applied in a given year. To correspond with the herbicide program classes in Weed Manager, the following delimiters were used: Ratio_TFI_Herb < 0.5 defines the low herbicide program, 0.5 ≤ Ratio_TFI_Herb < 1 defines the medium herbicide program, 1 ≤ Ratio_TFI_Herbi < 1.5 defines the high herbicide program, 1.5 ≤ Ratio_TFI_Herbi defines the very high herbicide program. Similarly, Ratio_Sowing_Date was used to categorise each year to an early, mid, or late sowing date, using Ratio_Sowing_Date < -0.2 to define an early sowing date, and Ratio_Sowing_Date > 0.2 to define a late sowing date.

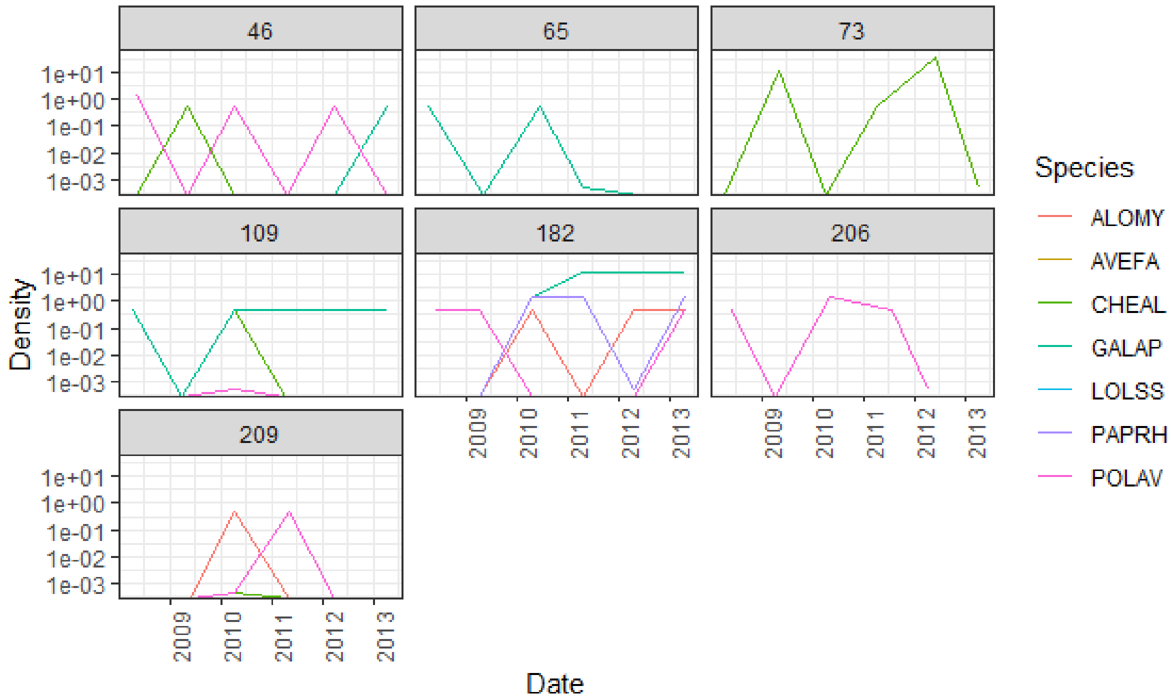

Figure 1. The density of weed seeds (on a log scale) from Yvoz et al., (2020) over time. Each plot depicts the density in a single rotation, with a unique crop rotation and management scenarios. Where a line is not shown, the reported density was 0 seeds per m^2.

4.2.6 Validation procedure

Validation was assessed by simulating each of the above 7 rotations for each of the weeds independently (as weed density was very low, we assume there is essentially no interaction between the weed species). The initial weed seed density was taken to be the initial observed seed density divided between the two soil layers, or where 0 seeds per m^2 were reported we used 0.0001 seeds per m^2, with 20% of those seeds in the shallow layer and 80% in the deep layer (proportional to the depth of each layer).

As the weed density values were small, binned, and zero-dominated (245 of 287 density observations were zero), validity was assessed as the proportion of cases in which Weed Manager correctly predicted a rise or fall in the weed seed densities.

The use of a DSS is expected to either increase the economic return to the grower or decrease the environmental impact through reduced use of herbicides. To explore the value of using Weed Manager, the rotations described in the papers were loaded into Weed Manager, and the simulated optimal management scenario was generated. The difference between the optimal expected financial return and that simulated using the management program given in the paper is then reported.

5 Results

5.1 Economic and environmental potentials of IPMWise

The economic and environmental potential of IPMwise (as well as input from farmers and agronomists on the agronomic practicalities of the recommendations), have been studied by use of field validation trials. Such trials are complicated and costly to execute, but a usual requirement by farmers and crop advisors in many countries, before new IPM tools are used in practice. Usually, requirements for agronomic robustness relating to weed control in arable crops are defined as: no yield loss in actual crop and no/low propagation of weeds.

In associated work, field validation trails have been executed with IPMwise and predecessors, in Denmark, Norway, Germany, Spain and Greece. In the sections below, results from each country are summarized.

5.1.1 Denmark

5.1.1.1 Potential savings for field-specific use of predecessors of IPMwise

In 1989–2006, more than 2,000 field validation experiments were executed by the Danish Agricultural Advisory Center, now 'SEGES', to test predecessor versions of IPMwise in plot trials, where local 'best standard' treatments were used as reference. These tests included the most important crops, which were spring- and winter cereals, sugar beet, maize, and peas. In cereals, which are grown on the largest areas relatively, a comprehensive study was executed in 2003-2006 to quantify the economic and environmental potential of Crop Protection Online, which is the 3rd generation predecessor tool. This work was sponsored by the Danish Environmental Protection Agency (Danish EPA), as a part of the Danish Pesticide Action Plan in those years. In this study, one objective was to quantify economic and environmental potentials of DSS for both weed- and pest/disease control (Jørgensen et al., 2007).

A general conclusion on the separate module for weed control was that while maintaining usual requirements for agronomic robustness, in terms of no yield loss and no/low propagation of weeds, the amount of herbicide used could be reduced by a minimum of 40%, which were equal to environmental savings in terms of Treatment Frequency Index (TFI).

The actual economic savings were 54 DKK/ha (~7.25 EURO/ha) in spring cereals and 137 DKK/ha (~18.39 Euro/ha) in winter cereals. Based only on the efficacy target values and dose-response calculations for herbicides included in this DSS, in additional crops (beet, maize, oilseed rape, grasses and clovers) an approximate potential of 20% reduction of herbicide use was estimated for such crops (Rydahl, 2021). As these field trials were executed in separate fields, the calculated potential may be interpreted as a potential for field-specific use of IPMwise.

5.1.1.2 Analyses of barriers against implementation

In the same project, a sociological study was included to analyze possible barriers against a wider uptake and exploitation of the measured potentials of this DSS (Jørgensen et al., 2007). In terms of uptake, this DSS is one of the most successful in Europe, as around 150 crop advisors (100%) and 750 farmers (3%) subscribe to this DSS (Been et al., 2009). However, results from the sociological study indicated that the need for manual field inspections constitutes a major barrier for a wider uptake (Jørgensen et al., 2007). In this context, logistic calculations indicate that crop advisors can only inspect relatively few fields. Consequently, to exploit the potential, it is essential that farmers can deliver reports on weed infestations in their own fields.

Accordingly, the 'RoboWeedMaps' technology was developed in Denmark, where currently 84 fields have been systematically photographed. Weed infestations were determined by machine learning algorithms (ML), supplemented by virtual field inspections using photographs. This resulted in linked data on weeds species, growth stages and densities in each field. When compared to the farmer's standard herbicide treatment, using IPMwise resulted in reductions of 57-73% in herbicide costs for various winter cereals. However, further development of the ML algorithms and additional field validation is required to assure robustness and realise the economic/environmental potential of this technology.

5.1.2 Norway

Field trials where the Norwegian version of IPMwise and processors were tested in 15 field trials in spring barley / spring wheat in 2003–2004. Three prototype versions, representing 3 levels of threshold/efficacy targets were tested, where the medium level resulted in 6% total residual weed cover at harvest time. This version was subsequently released officially. Compared to Norwegian 'best practise' as recommended by crop advisors, 38% reduction of cost of herbicide input was measured (Tørresen et al., 2004).

In 2005-2006, additional field validation experiments were made in 10 field trials, where only efficacy was measured. Compared to Norwegian 'best practise' as recommended by crop advisors, 27% reduction of cost of herbicide input was measured, while the achieved levels of efficacy were 92-100%, which were significantly higher than required by the DSS on most of the occurring weeds. These relatively high levels of efficacy were caused by co-incidental effects, due to presence of certain weed species, which released relatively high input of herbicides (Netland et al., 2006).

5.1.3 Germany

Field validation trials, where the German version of IPMwise were tested against local 'best practice' herbicide treatments were executed in 2016-2021. In total, 20 trials were executed in winter cereals, and 28 trials were executed in maize. In winter wheat and maize, no yield loss was measured and weed control was sufficient. Cost reductions of herbicides was 50-60%, while reductions of the Treatment Frequency Index (TFI) was approximately 50% (Bückmann et al., 2020).

5.1.4 Spain

Field validation trials include mainly cereals and maize, where 'best practice' treatments as determined by crop advisors, were used as references. In wheat, 17 field validation trials were executed in the years 2010-2013, where achieved efficacy was measured. In 2013, 3 field trials were executed, where also yields were measured.

No yield loss was measured, and sufficient weed control was measured. The reduction of herbicide input varied in terms of TFI, varied from 19.8% to 66% with a weighted average of 36%. (Montull et al., 2014; Montull, 2016). In maize, field validation trials were done in the years 2016 to 2019 (10 fields), and in soyabean during year 2021 (2 fields) (Montull, 2021).

Weed control was equal by IPMWise and by 'best practice' treatments, as proposed by advisors. Yield was not estimated, because there were no residual weeds in any treatment. Based on these results, it was assumed also that there were no yield losses. In maize and soybean. the reduction on herbicide input varied from 12.5 to 50%, but in general, weed infestations were high due to monocrop culture (no crop rotation), where it is generally difficult to diminish weed infestations significantly over time.

5.1.5 Greece

In 2020-2021, the first field validation trials with a Greek prototype of IPMwise for weed control in Greek wheat was executed in frame of the IPM Decisions project. This work is also part of a PhD study. See delivery 4.7 for more details.

5.2 Results from the analysis of Weed Manager

In this section we report on the validation of Weed Manager, and simulate the potential value of using Weed Manager, by comparing the optimized management program with the management scenarios used in the field.

5.2.1 Weed Manager validation

Of the 287 observed data points, there was a reported decrease in the weed seed density in 33 observations, and an increase in 34 observations. Of these, Weed Manager correctly predicted the direction in 76% of observations (Table 1).

Table 1. The proportion of simulated years in which the seed bank density either increased, stayed the same, and decreased when the observed seed bank density either increased or decreased.

		Simulated		
		Increase	No change	Decrease
Observed	Increase	0.71	0.03	0.26
	Decrease	0.18	0.00	0.82

The value of Weed Manager can either be presented as economic (the difference in net income predicted when using the optimized management scenario compared to using the field management), or environmental (for example a reduction in herbicide usage).

Economically, the use of the optimized management results in an increase in the median net income of 106 €/ha (Figure 2), primarily by reducing the amount of herbicide applied and sowing early. This management is suggested by Weed Manager as the weed density is generally too low to significantly result in substantial yield loss. Environmentally, Weed Manager suggests a significant reduction in herbicide program intensity (Figure 3).

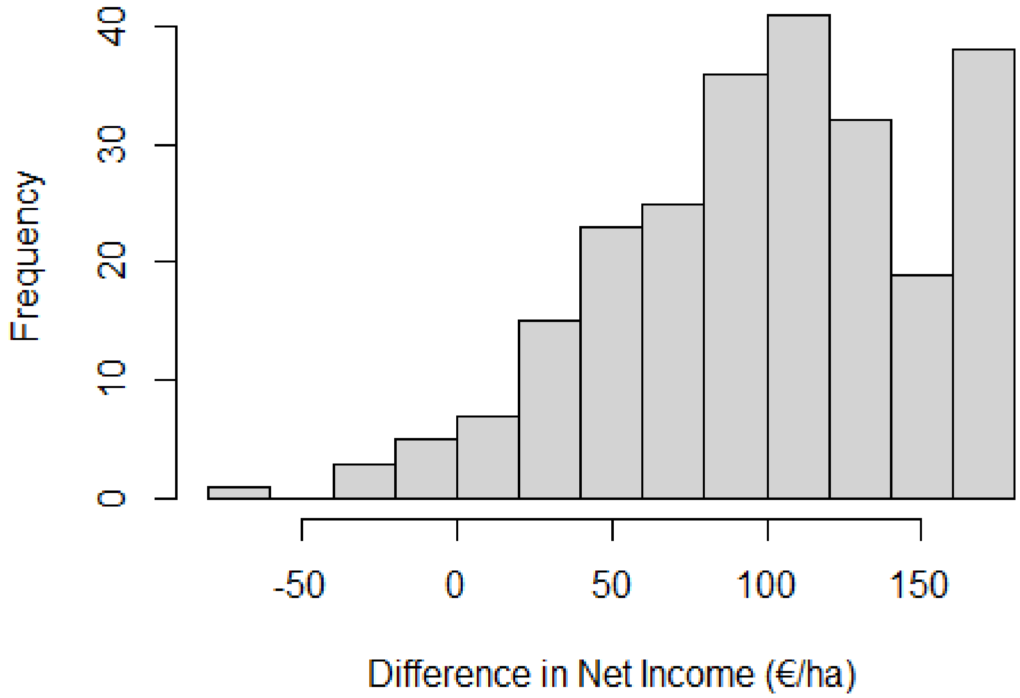

Figure 2. The frequency distribution of the median difference in net income ($V_{opt} - V_{obs}$) between the Weed Manager-predicted optimal management (V_{opt}) and the field management as given in the data (V_{obs}). Each instance compares the effect of the optimal and field management in one year of one of the seven rotations recorded in the dataset and one of the weed species.

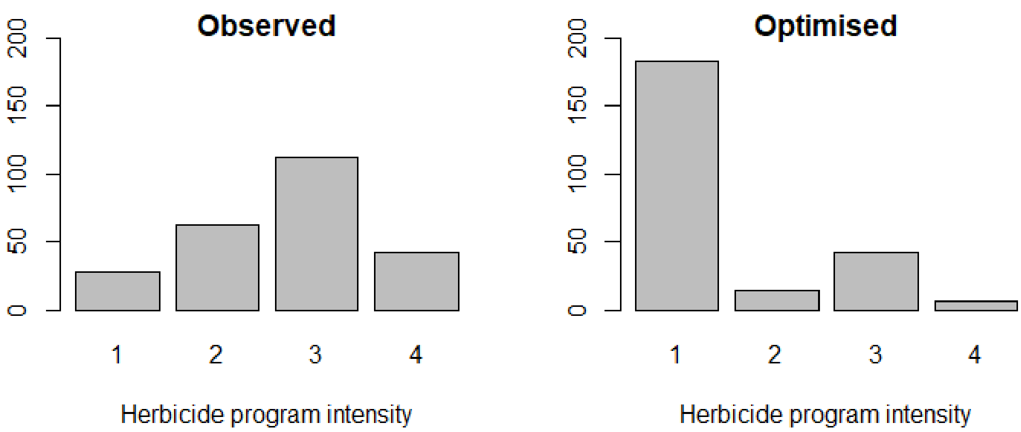

Figure 3. The distribution of herbicide program intensity observed in the field (left) and that suggested by optimizing management using Weed Manager (right). Again, each instance is the observed (left) and optimized (right) herbicide program intensity in a single year of the seven rotations.

6 Discussion

Both IPMWise and Weed Manager aim to enable growers to improve the efficiency of their management programs, IPMWise suggesting what herbicides and herbicide rates can achieve control which ensure yield potentials and low residual weed infestation of a wide variety of weeds in an expanding list of crops. The robust evidence base and validation work underlying this system means recommendations can be implemented with confidence. Weed Manager is primarily a tool for suggesting more generic management programs over a longer-term view of control. As such, its current application is in the exploration of scenarios that can be used to guide research and facilitate discussions with practitioners about improving the resilience of their cropping systems to weeds. A more resilient cropping system is expected to afford greater opportunities for reducing herbicide use, using systems such as IPMWise.

As the DSS are used in more places, particularly where conditions are different from where they were developed, it is necessary to ensure that they remain relevant to the conditions. In this document we have demonstrated several validations of IPMWise, and validated Weed Manager on a new dataset from France. Both DSS suggest that considerable reductions in herbicide use are possible, without significant loss of yield or income, in line with Integrated Pest Management (IPM) principles. In the following section the compliance of IPMWise is demonstrated against the range of IPM principles.

6.1 Compliance of IPMWise and Weed Manager to general IPM principles

According to Directive 2009/128/EC, Annex III, 8 general principles of IPM, which includes IWM, have been defined. Below, we assess IPMwise and Weed Manager against these 8 principles.

6.1.1 Use preventive measures, such as crop rotation, cultivation practises, balanced fertilisation, etc to suppress harmful organisms.

As some of these measures need to be addressed by farmers, or higher levels than the level of weed management, e.g., production of feeds for animal production, and use of fertilizers to achieve special qualities of yield.

IPMwise: No; Weed Manager: Yes

6.1.2 Use of monitoring of harmful organisms

Both DSS require input of field registrations of weed infestation in terms of combinations of weed species and accompanying classes of weed growth stages and -density.

IPMwise: Yes; Weed Manager: Yes

6.1.3 Use of threshold levels of infestations

IPMwise uses threshold values for combinations of crop, season, weed species and classes of weed density, to determine if control is needed or not of individual weed species. When a threshold value has been exceeded, increasing values of 'efficacy targets' (relative efficacy in percent, 3-4 weeks after application of a measure for control), will be used for exceeding weed densities. Weed manager responds to predicted levels of weed infestation and how they impact yield.

IPMwise: Yes; Weed Manager: Yes

6.1.4 Preference of non-chemical methods for control

IPMwise includes mechanical methods for control, which like herbicides will be recommended, when efficacy data document that some specific mechanical method can meet values of efficacy targets on specific weeds. Mechanical options will be sorted along with herbicide options, according to the user's selected method for optimisation and sorting: cost, TFI or ELI. Where mechanical methods will be preferred, when sorting for TFI / ELI.

Weed Manager considers the impact of sowing time, crop competitivity and cultivation on weed control.

IPMwise: Yes; Weed Manager: Yes

6.1.5 Targeted use of pesticides

IPMwise use continuous dose response functions (equations) ranging from 0 to 100% efficacy, where parameters are estimated for combinations of crop, season and weed species. Due to differences in values of efficacy targets, and differences of in susceptibility to specific herbicides, doses of herbicides may vary from 10 to 100% of the registered dose rates. Based on these calculations 2-4 way herbicide tank-mixtures will also be used to identify treatments on the field level with minimum input of herbicides (cost, TFI or ELI).
Weed Manager considers reduced dose but not specific products

IPMwise: Yes; Weed manager: partially

6.1.6 Use of pesticides on levels that are necessary, while also considering protection against new herbicide resistance development

Use of herbicides on levels that are necessary is addressed under paragraph 5, while herbicide resistance management is addressed under paragraph 7.

IPMwise: Yes. Weed Manager: Yes

6.1.7 Use of anti-resistance strategies

IPMwise includes two measures for herbicide anti-resistance management:

6.1.7.1 Control of already herbicide-resistant weeds

IPMwise and Weed Manager consider herbicide resistant biotypes of weeds as separate 'species', identified by use of the usual name + indication of actual mechanism of resistance, which refer often to specific mode-of-action (MOA). For example: 'Stellaria media, ALS-r'.

For such resistant biotypes, IPMwise will aim for effective sanitation by use low threshold values of weed density and high values of efficacy targets.

In addition, estimates of dose-response parameters of herbicides containing such MOA will be used, which ensure that efficacy of the registered (maximum) dose will <5%. After that IPMwise will be forced to automatically selection of herbicide products, which contain alternative MOA.

For co-formulated herbicide products of risky and non-risky MOAs, efficacy data will be looked up, if possible (by the national administrator of IPMwise), which document the efficacy of only the non-risky MOAs in a formulated product. In case such documentation cannot be provided, co-formulated products will be excluded for control of weed with such resistance.

6.1.7.2 Measures to prevent/delay new herbicide resistance

Unfortunately, results from research in generation of new herbicide resistance, are yet not clear in terms of predicting risks from use of different sequences of herbicide application. Consequently, IPMwise currently recommend the general strategy of using risky MOAs alone in maximum every 2nd generation of weeds.

IPMwise presents a list of current both risky and yet non-risky MOAs, which occur in current herbicide products.

According to field history, the user of IPMwise may determine to exclude some risky MOAs in a current field, so that only solutions using alternative (and yet safe) MOAs will be presented. Alternatively, the user may select to exclude such risky MOAs only when: 1) used alone or 2) risky weeds do not occur. These decision algorithms were developed in close collaboration with university partners in Norway (NIBIO), JKI (Germany), UdL (Spain) and European representatives of crop protection companies.

However, particularly in some minor crops, where only relatively few herbicide products are available, exclusion of some risky MOAs may completely obstruct recommendation of herbicide treatments. Accordingly, the user may determine to use a risky MOA in 2 or more years, and then keep in mind to 'restore' later by use of alternative MOAs.

Weed manager encourage an IWM approach and therefore implicitly addresses issues related to resistance management.

IPMwise: Yes; Weed Manager Yes.

6.1.8 Check success of applied measures for control

IPMwise recommend fields inspections 2-3 times during a growing season, where both surviving weeds after control and new flushes of weeds must be registered.

Weed Manager encourages the user to update observations annually.

IPMwise: Yes. Weed Manager: partially

In summary, IPMwise specifically complies to 7 out of 8 IPM principles as in Directive 2009/128/EC, Annex III. Weed Manager similarly promotes IWM and the principles of IPM.

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