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IPMwise – economic potential in 4 European countries of a generic decision support system for integrated weed management

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Abstract.

Driven by political action plans in Denmark, which were initiated in the 1980ies, and which aimed for reducing dependency on- and use of pesticides, a series of nationally funded R&D programs were executed in the period 1989-2006. One output was a 'decision support system' (DSS) for integrated weed management, which has the product name 'IPMwise'. A fundamental idea behind this DSS is to systematically exploit that 1) the occurrence of weeds differs in time and space and 2) weeds differ in terms of need for control and susceptibility to herbicides.

Accordingly, optimization in this domain should enable substantial reductions in herbicide input, without jeopardizing usual agronomic requirements for weed control. Using results from field scouting as input, IPMwise can:

- *Quantify needs for control*
- *Identify single herbicide products and calculate dose rates by use of a dose-response equation, which has been parameterized by use of publicly available efficacy data. Simultaneously, legal restrictions on the herbicide product level will be respected*
- *Compose and optimize (minimize cost, TFI or similar index) 2-4 way tank mixtures*
- *Recommend specific mechanical control, yet only in cases, where herbicides are sparse/less competitive*
- *Assist herbicide resistance management*

Initially in Denmark, several DSS prototypes were constructed, and field tested. In the 2000ies, *efforts were initiated to also export this DSS design. While maintaining original equations/algorithms, total re-customizations were made of agronomic-, legal- and lingual content to match national conditions. For crops of major importance, full assortments of weeds and herbicide products, were included. The numbers of included crops are currently: Denmark 32, Norway 6, Germany 3 and Spain 19.*

While respecting national requirements for robustness in weed management, results from field validation trials show that the cost/TFI of herbicides was reduced by 20-50% as compared to 'local best practice' treatments. Accordingly, this DSS concept is expected to have potential also for additional scaling.

However, the need for manual weed scouting has been identified as a major obstacle for a wider use of this DSS. This subject is addressed in another paper presented at this conference (Rydahl et al., 2022).

Keywords.
Integrated weed management, decision support system, herbicide dose-response function, line-ar optimization, system export, IPM principles

Introduction

Since the introduction in the 1950ies of phenoxy-acids, as new options for selective weed control, farmers have requested support on how to properly manage these products and a substantial number of additional products, which have been introduced since then.

In Europe, a widespread method used to identify suitable strategies for weed control, is to engage with crop advisors, whom farmers trust to have sufficient overviews of agronomic, legal and economic issues. They supply regionally adapted, crop specific treatment plans to the farmers for the most common weeds, pests and diseases. In case of less satisfactory control in field, feed-back routines are practiced, to adjust treatment plans for coming growth seasons.

To support identification of such treatment plans, national field trials are conducted in fields, where relatively heavy weed infestations are expected, to test yield response and efficacy of various treatment plans, which mean combinations of timings, herbicide products and dose rates. Result from such trials, combined with information on product labels forms the basis of provision of crop- and region-differentiated treatment plans for weed control.

However, to achieve sufficient control in most fields, such treatment plans need to be relative conservative. Accordingly, a systematic overkill will be achieved in most fields in a region, which is caused mainly by the following conditions (Montull et al., 2020):

- Weeds are unevenly distributed in time and space
- Weeds differ in 'noxiousness' and therefore also in needs for control, e.g. for different combinations of countries and crops
- Weeds differ in susceptibility to herbicides, as some species can be controlled sufficiently by down to 10% of registered dose rates, while other species need 100% or more, which may require also use of tank-mixing

Accordingly, in theory, considerable both economic and environmental potential exist for design and implementation of a new principles for decision making, which respond to actual weed infestations. This may be achieved by transferring decision making from now regional levels to farm- and field levels.

However such transition must still respect farmer's existing requirements for agronomic robustness, manage continuously changing supplies of herbicide products and ensure also compliance to still more complex and comprehensive legal restrictions for use of pesticides.

To rationally manage and optimize in this domain, design, construction and field validation of computer based 'Decision Support System' DSS to support Integrated Weed Management (IWM) was initiated in Denmark in 1989. The newest DSS for IWM, known as 'IPMwise', was delivered by IPM Consult in 2016 (Rydahl and Bojer, 2016).

Methods

IT basis and stages of agronomic development

'IPMwise', which is a 4th generation tool in terms of IT and agronomic models. It is distributed by Datalogisk A/S, which also provides a Farm Management System called 'Naesgaard Mark'.

A 3rd generation predecessor system is still running in Denmark. Compared to this, IPMwise includes new and unique features for: herbicide resistance management, options for recommendation of specific methods for mechanical control, treatment maps for site-specific weed control and more.

By remote access, appointed 'national administrators' can edit national versions of IPMwise by use of remote access. A national version may include simple prototypes for new developments, a test version for functional- and field validation test and official versions, upgraded regularly after functional test of the test version.

Equations and decision algorithms

Based on a field report on weed infestation (combinations of weed species, classes of weed density and classes of weed growth stages), the technical 'back-bone' / 'decision engine' of IPMwise contains various components used for calculations and presentations.

The first step is to evaluate needs for weed control, which is provided by a simple equation, which provides a continuous relation between density of various weed species and target efficacy in percent, which refers to efficacies, which can be measured 3-6 weeks after treatment. This equation uses also threshold values of weed density, which must be exceeded to initiate use of the equation, i.e. deliver values of efficacy target >0.

To meet specific values of efficacy target, Equation 1 (Montull et al, 2020) is used, which generates a continuous relation between herbicide dose rate and relative efficacy.

$$Y = \frac{1}{1+\exp(-2(a_w + b_h(\log(\frac{x}{r_s * r_t * r_w})}) \qquad (1)$$

where:

Y	is the relative efficacy, e.g. in percent [%]
b_h	is a parameter describing the 'slope' at ED_{50}, specific for an herbicide
a_w	is a parameter describing the horizontal displacement specific for a weed species
X	is the dose
r_s, r_t, r_w	are parameters of relative potencies (= 'dose rate factors'), which quantify the relative correction of dose rate, due to weed growth stage, temperature/Rh and drought stress, respectively, as compared to reference points, determined by reference values registered, when efficacy data on weed species were produced

By use of Equation 1, dose rates of single herbicides will be calculated for the reported weeds, which occurred in so high densities that values of efficacy target >0 was found.

Such calculated dose rates are then forwarded to the so-called 'Additive Dose Model' (ADM) (Streibig et al., 1999), which use the math principle of 'linear optimization' to minimize cost- or Treatment Frequency Index (TFI) of herbicides for a certain weed infestation, in terms of 2-4 way herbicide tank-mixtures. In Fig 1, a graphical illustration of ADM is provided.

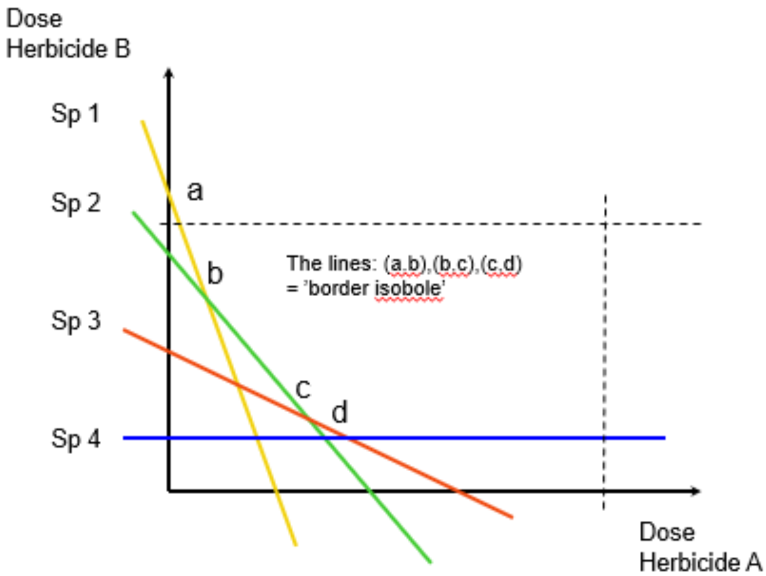

Fig 1 – Graphical illustration of identification of an optimized tank-mixture by use of ADM for 2 herbicides and 4 weeds

Notes:
1) for each weed and herbicide, doses of single products have been calculated by use of Equation 1
2) dotted lines indicate registered (maximum dose rates
3) each weed species needs a specific level of efficacy, which represented by 4 straight lines, which are also referred to as 'isoboles'
4) the 4 straight lines assume that no significant synergistic or antagonistic effects occur, when mixing these 2 herbicides
5) optimums (minimums) will typically be in 1) interceptions between max doses and isoboles, 2) interceptions between 2 isobloles, e.g. as illustrated by points a-d
6) the isobole for Sp 4 indicates that no efficacy data is available of herbicide A for this weed, why a very high dose is assumed
7) in case of 3-way mixtures, line-isoboles will be replaced by 3-dimensional planes, where minimums can be found in intercepts. In case of 4-way mixture, no graphical illustration can be made, but minimums can be found by solving equations.

For all both single herbicides and tank-mixtures, adding of adjuvant product will be provided automatically according to specific algorithms.

Measures for managing herbicide resistance

According to reports from Herbicide Resistance Action Committees (HRAC, 2022) herbicide resistance is getting still worse in terms of 1) affected herbicide mode-of-action (MoA) and numbers on incidents. IPMwise address these problems on 2 levels: 1) control of already resistant biotypes and 2) delay of new resistance development.

Control of already resistant biotypes of weeds is managed in IPMwise by use of 1) relatively high values of efficacy targets and 2) use of estimates of herbicide dose-response parameters (Equation 1), which provide a low efficacy (<5%) of the registered (maximum) dose rates on such biotypes. When reporting such biotypes to 'IPMwise', herbicides with alternative MoA will be auto selected to meet efficacy targets.

Measures to prevent / delay develop new herbicide resistance include:

- A textual introduction, which explain which herbicide MoAs that has already been found substantial cases of resistance to in the actual country (HRAC, 2022), and which therefore have been classiffied as 'particularly risky' and a general recommendation to use such in maximum every 2nd generation of weeds
- A cross-table, which shows the actual herbicide product names and their content of different MoAs
- Options for the user to switch on/off recommendation of such 'particularly risky' MoA,

as documented by field history. When switched off, the user is invted to select 2 modifications/exceptions:

- Exclude only when used alone, i.e. co-formulations and tank-mixes with alternative and still safe MoAs can still be suggested
- Exclude only when the field has weed species, which are considered particularly vulnerable to development of herbicide resistance, according reports (HRAC, 2022)

The core of these principles has also been implemented for use of mechanical weed control, as on/off use of specific methods, in situations where values of efficacy targets can be met. However, yet mechanical options for control have only been included in selected crops and crop growth stages, where the supply of herbicides are insufficient or particularly costly. Such as for example late treatments of big weeds in maize and sugar beet.

Customization for national conditions

Currently, IPMwise has been customized for commercial use in Denmark, Norway and Spain, and soon a version for commercial use in Germany will also be released. Initial customization has been made also in Greece.

In each of these countries, national administrators have been appointed, which take responsibility for customization for national conditions, which may include:

Compulsory customizations:

- Minimum 1 user-interface (UI) language
- A selection of important crops, weed species and herbicides
- Provision of herbicide efficacy data for estimation of dose-response parameters

Additional, optional customization may include parameters and herbicide dose corrections on:

- classes of weed growth stages
- min/max temperatures on day of spraying
- classes of drought stress
- herbicide resistance management
- mechanical control

In some of these parameters are not estimated, minimum requirements should be instead provided as specific text remarks.

Data/information on expected efficacy of different herbicides, in different crops against different weed species are provided from various sources in each country. In Denmark, so-called ‘EU registration reports, Part 7’ are publicly available. These contain trans-scripted and summarized efficacy data, which producers of agrochemical products submit to authorities, when applying for registration. In Norway, the University NIBIO in collaboration with the national advisory service executes a lot of efficacy trials, where new herbicide products are field tested in 2-3 dose rates, from which data are publicly available. In Germany and Spain, the IPMwise partners get access to efficacy data in collaboration with national providers of herbicide products.

In general, real data on herbicide efficacy can only be expected in crops, where substantial areas are cultivated. In ‘minor’ crops, the only information available may be readings from herbicides product labels. However, IPMwise is structured to integrate such various sources of data and information, which is handled by the national administrators, which are also trained to integrate safety margins, aiming for suitable agronomic robustness. When relatively big datasets are available, statistical methods may be used, but when datasets/information is sparsely, only ‘expert evaluation’ will be used.

It has been generally realized that only parts of combinations of countries, crops, herbicides, weeds, etc. can be supported by practical recommendations, irrespective of using IPMwise or alternative methods. Therefore, on weeds which occur only occasionally, only sparse data/information will be available. The focus by the national administrators is to ensure that all available documentation has been collected and integrated in a way, where use of safety margins shall secure that no false recommendations are provided. Previous Europeand DSS for IPM, which ignored this aspect, have suffered a ‘sudden death’ (Been et al., 2009).

In Tab 1, an overview of levels of customization of IPMwise in 4 countries is provided

Tab 1 - Main customization of IPMwise in 4 countries

Country	Crops	Weeds, inclusive resistant biotypes	Herbicides, inclusive generics	Dose-response combinations for crops, herbicides and weeds	Tank-mixtures, 2-4 way
Denmark	32	120	104	20,787	374
Norway	6	49	41	2,937	267
Germany	3	87	144	2,913	554
Spain	19	175	182	21,005	1,772

In Greece. a PhD study is currently in progress, where initial customization and field validation of IPMwise for use in Greek wheat is executed.

Results

Available online tools for users

The Danish version IPMwise is full-functioning in both Danish and English user-interface. This includes 4 main tools for calculations, which are all run by the same decision algorithms and equations:

- *‘Consultation’*
  The user enters: a field report on weed infestation, and preferences. The tool returns as many options for control as possible, which meet values of efficacy target. Such include both single herbicides, tank-mixtures and adequate adding of adjuvants
- *‘Profile’*
  The user selects a combination of crop, crop BBCH stage, season (autumn/spring), classes of weed size, temperatures and drought stress and herbicide name. The tool returns calculations of expected efficacy on as many weeds as possible under varying conditions
- *‘Mixture’*
  The user selects the same conditions as in tool Profile but now with up to 4 herbicide products and dose rates for tank-mixing. The tool returns expected efficacy of the mixture and the mixing components, under varying conditions
- *‘Overview’*
  The user selects the same conditions as above and a selection of weed species. The tool returns in the actual crop and season an overview of all herbicides, BBCH stages for use, maximum doses and expected efficacies.

In Fig 2-6, examples are provided from use of these tools in the Danish version of IPMwise, in English/Latin user-interface. In Norway and Germany, IPMwise is available only in native user-interface languages, while in Spain also an English UI can be used.

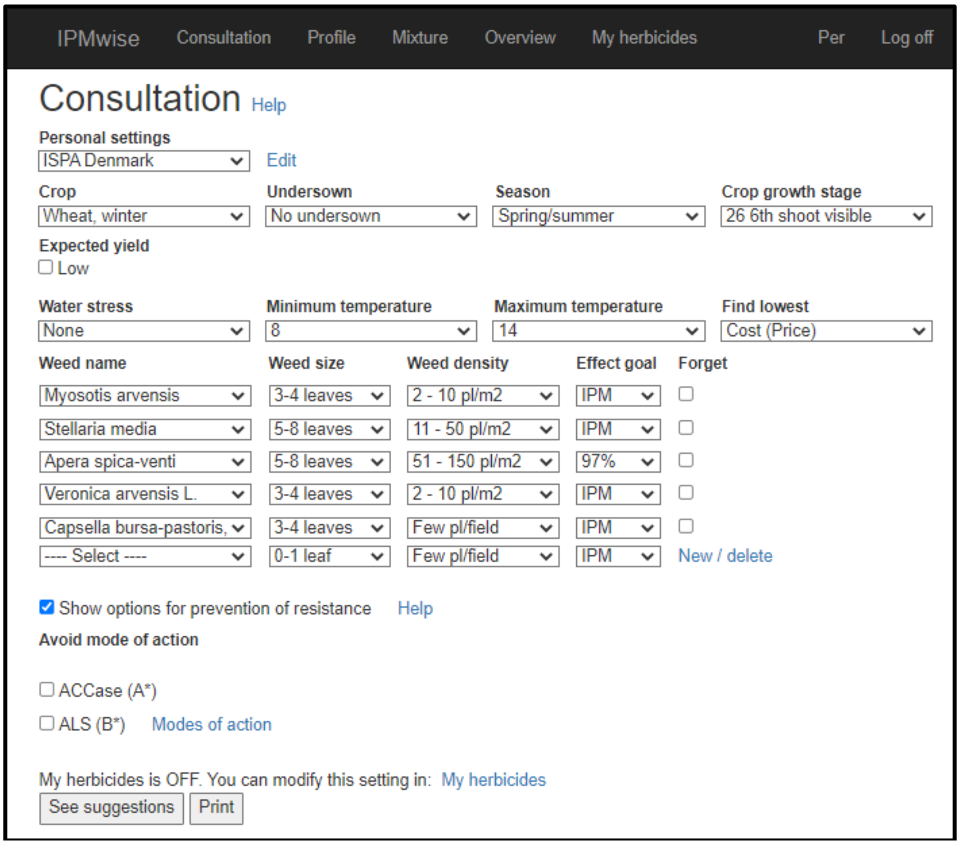

Figure 2 - Example of user-input to tool 'Consultation'

Notes:

1) The user overruled the default IPM efficacy target of Apera spica-venti to 97%.

2) The user has not reported any already herbicide resistant weed biotypes

3) The user has not excludec use of 2 MoAs (ACCase and ALS), which have already been found in a substantial number of cases (HRAC, 2022), and which are therefore considered to be particularly risky in Denmark

Consultation © 2022 - IPM Consult ApS

Crop: Wheat, winter	Season: Spring/summer	Crop growth stage: 26 6th shoot visible
Water stress: None	Temperature: 8 °C - 14 °C	Temperature: 8 °C - 14 °C
Find lowest: Cost (Price)	Myosotis arvensis: 3-4 leaves, 2 - 10 pl/m2, 0%	Stellaria media, threatned of resistance to ALS (HRAC, gr. B): 5-8 leaves, 11 - 50 pl/m2, 84%
Apera spica-venti, threatned of resistance to ALS (HRAC, gr. B): 5-8 leaves, 51 - 150 pl/m2, 97%	Veronica arvensis L.: 3-4 leaves, 2 - 10 pl/m2, 0%	Capsella bursa-pastoris, B-r: 3-4 leaves, Few pl/field, 0%

Suggestions	Price (DKK/ha)	TFI	E-Load	MOA
Broadway (124 g) + PG26N (0.5 l)	168.12	1.02	0.05	B*

Tradename	Dose / ha	Max dose / ha	Unit	Price (DKK/ha)	TFI	E-Load	MOA
Broadway	124.448	130	g	143.12	1.02	0.05	B*
PG26N	0.5	0.5	l	25	0	0	

Weed name	Expected effect (%)	Desired effect (%)	Sufficient effect by IPM (%)
Stellaria media	96	84	84
Apera spica-venti	96	97	92

Suggestions	Price (DKK/ha)	TFI	E-Load	MOA
Othello (0.63 l)	189	0.9	0.21	B*
Serrate (0.12 kg) + Hussar Plus OD (0.039 l)	189.93	1.3	0.08	A*,B*,B*
Serrate (0.12 kg) + Atlantis OD (0.16 l)	191.95	1.26	0.08	A*,B*,B*
Serrate (0.12 kg) + Hussar OD (0.017 l) + Renol (0.5 l)	205.64	1.25	0.07	A*,B*,B*

Fig 3 - Output from tool 'Consultation', based on the input in Fig 2

Notes:

1) One Danish Crown (DKK) is equal to 0.14 USD.

2) Cost-minimized and -sorted top-5 options for control are presented

3) Solution no. 1, Broadway, contains 22.8 g/kg florasulam plus 68.3 g/kg pyroxsulam. A special adjuvant PG26N has been added.

4) For the cheapest solution (No. 1), Broadway, efficacy calculations have been opened. These show that in the actual field, only 2 out of 5 entered weeds occurred in densities which required control

Profile © 2022 - IPM Consult ApS

Herbicide:	Crop:	Season:
Atlantis OD (0.9 l)	Wheat, winter	Spring/summer
Crop growth stage:	Weed size:	Water stress:
6th shoot visible	3-4 leaves	None
Temperature:		
8 °C - 14 °C		

Weed species	Efficacy at 5 doses				
-	1/8	1/4	1/2	1/1	(2/1)
	0.1125	0.225	0.45	0.9	1.8
Aethusa cynapium L.	4	13	33	62	84
Alopecurus myosuroides	45	73	90	96	99
Alopecurus myosuroides, A+B-r	45	73	90	96	99
Alopecurus myosuroides, A-r	45	73	90	96	99
Alopecurus myosuroides, B-r	45	73	90	96	99

Fig 4 - Example of output from tool 'Profile'

Notes:
1) In the top section (dimmed), the user selections of conditions for calcualtions are presented
2) Atlantis OD contains 30 g/l mefenpyr-diethyl, 2 g/l iodosulfuron-mehtyl and 10 g/l mesulfuron-methyl
3) Alopecurus myosuroides occurs both as a normal species and as 3 already herbicide resistant biotypes
4) The efficacy Profile of Atlantis OD includes a total of 46 weeds/biotypes

Mixture © 2022 - IPM Consult A

Herbicide:	Herbicide:	Herbicide:
Atlantis OD (0.45 l)	DFF (0.12 l)	Serrate (0.06 kg)
Crop:	Season:	Crop growth stage:
Wheat, winter	Spring/summer	6th shoot visible
Weed size:	Water stress:	Temperature:
5-8 leaves	None	8 °C - 14 °C

Weed species	Effect			
-	Mixture	DFF	Atlantis OD	Serrate
Aethusa cynapium L.	32	0	32	0
Alopecurus myosuroides, A+B-r	90	0	86	9
Alopecurus myosuroides, A-r	90	0	86	9
Alopecurus myosuroides, B-r	91	0	86	22
Anagallis arvensis L.	78	78	0	0

Fig 5 - Example of output from tool 'Mixture'

Notes:
1) Calculations of expected efficacy on a tank-mixture as composed by the user, which includes 3 herbicides, each in 50% of the registered (maximum) dose rates
2) in this case only alphabetic sorted top-5 weed species/resistant biotypes have been included, while the total number was 53 weeds/biotypes.

Overview © 2022 - IPM Consult ApS

Crop:	Season:	Weed density:
Wheat, winter	Spring/summer	11 - 50 pl/m2
Weed size:	Water stress:	Temperature:
3-4 leaves	None	8 °C - 14 °C
Relative dose:	Effect:	
1/1	Absolute effects (%)	

Herbicide	MOA	Growth stage	Max. dose	Dose	Price (DKK)	Alopecurus myosuroides	Capsella bursa-pastoris	Capsella bursa-pastoris, B-r	Chenopodium album L.	Lolium multiflorum
Nuance Max 75 WG	B*	11 - 29	5 g	5 g	23				79	
Express 50 SX	B*	12 - 29	13.5 g	13.5 g	36		92		86	
Ally 20 SX	B*	20 - 29	15 g	15 g	38		91		73	
Express 50 SX	B*	30 - 39	15 g	15 g	40		92		87	
Nuance Max 75 WG	B*	30 - 39	10 g	10 g	45				87	

***Fig 6* - Example of output from tool 'Overview'**

Notes:

[1)] Indications of expected efficacy may alternatively be presented as *-markings relating to efficacy targets as determined by classes of weed density
[2)] MOAs marked with a star, e.g. 'B*' indicates that HRAC class B, which is also referred to as ALS, is considered as 'risky', because substantial number of fields with this type of resistance has been reported nu the Scandinavian/Baltic department of HRAC

A set of supplementary tools have also been implemented:

- *Personal settings*
  Allow the user to save input conditions, e.g. weed infestation from previous years, 2) names of single herbicides and specific tank-mixtures, which may be relevant for use later
- *Users own herbicides*
  When enabled, tool 'Consultation' will searchy options for control by use only of this selection of herbicides and accompanying prices. For a regional crop advisor, this tool may provide overviews of optimal uses of herbicide products available in this region
- *Modes of action*
  With separate entry or entry from inside tool 'Consultation', this tool can inform the use on actual content of mode-of-action (MoAs) as a mean to avoid repeated use of MoA, which have already been found risk in terms of generating herbicide resistance (HRAC, 2022)
- *Weed identification key*
  This tool contains botanical descriptions and pictures of weeds in different growth stages, which may assist users in entering of field reports in tool 'Consultation' on weed infestations
- *Integration with the Danish Farm Management System 'Naesgaard Mark'*
  An Application Programming Interface (API) for IPMwise has been integrated with 'Naesgaard Mark', so users need only to login there to use the Naesgaard Mark-looking version of IPMwise.

Results from field validation trials

In most European countries, farmers and crop advisors request results from field test of new machinery, pesticides, crop cultivars etc., before they start using such. This situation is also affecting 'IPMwise', which therefore need to demonstrate both sufficient agronomic robustness and some potential. This means that data are requested on the use of IPMwise, which show no adverse effect on mainly 1) efficacy on weeds both 3-6 weeks after treatment, 2) yield and 3) residual weed infestation around harvest time, as an indication of effect on weed propagation.

To achieve a reasonable balancing between input of herbicides and in particular residual weed infestations at harvest time, initial field test often included 2-3 versions of thresholds/efficacy targets to identify suitable balancing. Below, a short summary of results from such final field tests in 4 countries is provided.

Denmark

In 1989–2006, more than 2,000 field validation experiments were executed by the Danish Agricultural Advisory Center, 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, silage maize and peas.

In cereals, which are grown on the largest areas relatively, a comprehensive study was executed in 2003-2006 to quantify 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 Danish Pesticide Action Plan. In this study, one objective was to quantify economic and environmental potentials of DSS for both weed- and pest/disease control.

A general conclusion on the module for weed control was that while maintaining usual requirements for agronomic robustness, in terms of no yield loss and no/low residual weed infestations (<10-15% total weed cover at harvest time), the amount of herbicide used could be reduced by a minimum of 40%, which were approximately equal to environmental savings in terms of the Treatment Frequency Index (TFI) (Jørgensen et al., 2007).

Norway

Field trials have been made, 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 no cases of yield loss and 6% total residual weed cover at harvest time. This version was subsequently released officially. Compared to Norwegian 'best practice' as recommended by crop advisors, 38% reduction of cost of herbicide input was measured (Torresen 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 practice' 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).

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).

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, 2022).

Conclusion

Since 1989, comprehensive studies were designed and executed in Denmark to firstly identify and quantify factors of major importance to herbicide efficacy. Which were found to be weed species, classes of weed growth stage, temperatures around time of spraying, drought stress, use of adjuvants and optimization of tank-mixtures (Jorgensen et alt, 2007; Montull et al., 2020).

Based on these results and results from regular field testing of new herbicides in 4 dose rates, plus testing in in greenhouses and climatic simulators, design and construction of computer based DSS for IPM/IWM was initiated. 'IPMwise' is a 4^{th} generation tool in terms of IT basis and agronomic models.

The backbone of IPMwise is a 3-step model, which based on a field report on weed infestation (species, sizes and densities) 1) determines values of efficacy target, which vary from 0 to 97% in the Danish version, 2) use a continuous herbicide dose-response function (Equation 1) to identify dose rates of single herbicides, which can meet the efficacy targets, and 3) investigate by the math principles of 'linear optimization', if 2-4 way cost-minimized herbicide tank-mixes are required to meet efficacy targes, or, can contribute furtherly to minimization of herbicide input..

According to the current estimates of involved parameters, IPMwise can adjust the input of herbicides from cero (when no control is required) to herbicide input ranging from 10% of registered dose rates of single herbicides, to ultimately 4 herbicides each in the registered dose rates. With thus 0,1 to 4,0 'full doses' as remedy, 'IPMwise' can find options for control in both simple and very complex weed infestations. However, still maybe not infestations, which include big infestation of weeds, where no/few efficacy data are available.

I Denmark, Norway, Germany and Spain, results from field validation plot trials in major crops of IPMwise and predecessors show that 1) yield potentials are secured when comparing to current 'best practice' treatments, 2) residual weed infestations are on acceptable levels, often specified as maximum 10-15% total ground cover of weeds at harvest time (Jorgensen et al., 2007), while input of herbicides have been reduced by 27-66% as compared to references.

Discussions have been taken with both Danish and European representatives of the crop protection industry, both on the general concept of 'IPMwise' and particular on possible risks connected to application of doses rates, which are lower than specified on product labels. In Europe, however, some consensus has been achieved to the perception that such discussions should be based on expected/achieved efficacy rather than specific dose rates, as any herbicide dose rate has both strengthens and weaknesses in terms of efficacy, according to calculations made by Equation 1 and ADM for minimization of input by tank-mixtures.

Based on the results achieved with 'IPMwise' and predecessors in 4 countries, this concept is expected to have significant potential for additional scaling.

A major bottleneck for such expansion has been detected in terms of reluctance among farmers to provide results from field inspections on weed infestations (Jorgensen et al, 2007). This challenge is currently being addressed by systematic photographing of fields and training of ‘machine learning’ to auto identify weed infestations, on the species level as required by IPMwise. Results from these developments will be presented in a separate paper on this conference (Rydahl, et al., 2022)

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References

Been T, Berti A, Evans N, Gouache D, Volkmar G, Jensen JE, Kapsa J, Levay N, Munier-Jolain N, Nibouche S, Raynal M, Rydahl, P (2009). Review of new technologies critical to effective implementation of Decision Support Systems (DSS’s) and Farm Management Systems (FMS’s) Aarhus University, Denmark, 6th March 2009. http://www.endure-network.eu/content/download/4803/39494/file/Review%20of%20new%20technologies%20critical%20to%20effective%20implementation%20of%20decision%20support%20systems%20and%20farm%20management%20systems.pdf

Bückmann H, Bojer OM, Rydahl P, Verschwele A, (2020). Application of a new Internet-based decision support model for integrated weed management in winter wheat and maize (DSS-IWM) - experiences from practical applications. Proceedings 29th German Conference on Weed Biology and Weed Control. Julius-Kühn-Archiv 464. 228-236.

Herbicide Resistance Action Committees (2022). https://www.hracglobal.com/

Jorgensen LN, Noe E, Langvad AM, Rydahl P, Orum JE, Pinnschmidt H, Bojer O (2007). Vurdering af Plantevern Onlines okonomiske og miljomessige effekt, 246 pages, with English summary in pp. 15-19. https://www2.mst.dk/Udgiv/publikationer/2007/978-87-7052-590-9/pdf/978-87-7052-590-9.pdf

Montull (2022). In preparation.

Montull JM, Taberner A, Bojer O, Rydahl P (2020). IPMwise: A Decision Support System for Multispecies Weed Control in Cereal Crops. In book: Decision Support Systems for Weed Management, Springer, Cham, pp 279-298

Montull, José-Maria (2016). Adapting the Decision Support System CPOWeeds to optimize weed control in northern Spanish conditions. PhD thesis, Universitat de Lleida, Departament d´Hortifructicultura, Botánica I Jardineria.

Montull, José-Maria; Soenderskov M.; Rydahl, P.; Boejer, O.M.; Taberner, A (2014). Four years validation of decision support optimising herbicide dose in cereals under Spanish conditions. Crop Protection 64 (2014), 110-114.

Netland J, Torresen KS, Rydahl P (2006). Resultat frå forsok med beslutningsstottesystemet VIPS-Ugras for ugrassproyting i haustkorn. Bioforsk FOKUS 1(3): 50-51.

Rydahl P, Bojer OM (2016). ‘IPMwise’, customized for conditions in Denmark (dk.ipmwise.com).

Rydahl P, Bojer OM, Jensen NP, Nielsen MP, Paz LC, Hartmann B; Andersen P, Jorgensen R, Sorensen M 2022). Economic potential of RoboWeedMaps – use of machine learning for production of weed maps and herbicide application maps. Proceeding of the 15th International conference on Precision Agriculture, June 326-29, 2022, Minneapolis, Minnesota, United states.

Streibig JC, Kudsk P, Jensen JE (1999). A general joint action model for herbicide mixtyures. Pesticide Science. Volume 53, Issue 1 p. 21-28 https://doi.org/10.1002/(SICI)1096-9063(199805)53:1<21::AID-PS748>3.0.CO;2-L

Torresen KS, Netland J, Rydahl P. (2004). Norsk utgave av det danske beslutningsstottesysstemet Plantevern Online for ugrassproyting i korn. In Gronn kunnskap 8(2) (pp. 100-109).