Spatial variability of optimized herbicide mixtures and dosages

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Abstract *Driven by 25 years of Danish, political 'pesticide action plans', aiming at reducing the use of pesticides, a Danish Decision Support System (DSS) for Integrated Weed Management (IWM) has been constructed. This online tool, called 'IPMwise' is now in its 4th generation. It integrates the 8 general IPM-principles as defined by the EU.*

In Denmark, this DSS includes 30 crops, 105 weeds and full assortments of herbicides. Due to generic qualities in both the integrated agro-biological models and in the IT setup, this DSS concept is currently being customized and validated for release also in Norway, Germany and Spain.

In these countries, results from field validation experiments with this DSS show that recommendations are sufficiently, agronomically robust, and has a yet unexploited potential for reducing the use of herbicides of 20-40%, as compared to references.

These potentials arise from exploitation, mainly of the following conditions: 1) weeds are unevenly distributed in time and space, 2) a complete weed kill is never required, 3) some weed species can be controlled sufficiently by down to 10% of a registered herbicide dose rate. In addition, the DSS can optimize the composition of 2–4-way tank-mixtures and thereby offer recommendations for a wide range of weed infestations.

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The lack of implementation and exploitation has been thoroughly investigated in sociological studies, where farmer's reluctance against manual weed scouting was identified as a dominating obstacle.

In a Danish project with the acronym name 'RoboWeedMaPS' (2017-20), these challenges are addressed by use of manual/automatic analyses of weed infestations, as detected from pictures and structured as required by 'IPMwise'.

Automated weed image acquisition and semi-automated weed annotation was used to feed 'IPMwise', where herbicide recommendations on herbicide application were achieved on three levels i.e. field level, on/off application in points, and full precision variable dose. The results demonstrated the potential savings of the three strategies compared to the farmers actual herbicide application, which in a closer examination by 'IPMwise' turned out to have unsatisfactory low efficacy on some important weeds. The result was transferred to an herbicide application map and the spatial variability was analyzed and evaluated. This showed a potential of 61% reduction of herbicide cost by changing decision making from the field level to a 10 x 10 m grid.

Keywords. *Integrated weed management, precision agriculture, application maps, herbicide mixtures, automated weed recognition, deep learning, 'IPMwise'.*

Introduction

Since the mid 1980ies in Denmark, factors affecting efficacy of herbicides were intensively researched. Such main factors were then used to design of herbicide dose-response models, where all ingoing parameters were also estimated. Additional R&D were made to develop methods to optimize herbicide tank-mixtures, to provide practical recommendations for weed control on the field level (Kudsk, 1989), and to promote dissemination and uptake, a DSS was designed and produced. The 4th and newest generation is named 'IPMwise' (Rydahl and Bojer, 2016), where also 8 general principles of IPM have been integrated as specified in Directive 2009/128/EC (European Parliament, 2009).

For tactical decision making during a growing season, the farmer/advisor will enter a field report holding the actual weed infestation into 'IPMwise', which will then subsequently process the following decision-making steps:

1. determine the need for weed control in terms of efficacy target values in percent. A value '0%' indicates that thresholds for control have not been exceeded. When thresholds have been exceeded, efficacy targets will vary, currently between 50-97%, depending on combinations of: country, crop, weed species, season (spring or autumn in countries, which have cold winters), classes of weed density. Exact values for released DSS versions were determined from field validation experiments, where DSS-prototypes requiring different levels of target efficacy, were compare to local 'best practice' treatments in terms of yield and residual weed infestation. During 1986-2006, >2,000 such field validation trials were made with DSS prototypes in Denmark (Rydahl, 2004).
2. identify candidate herbicide products and dose rates, which consider:
    a. legal restrictions on herbicide products
    b. the farmer's product preferences
    c. the farmer's preferred anti-resistance strategy according to the field history in the Farm Management System 'Naesgaard Mark' (Datalogisk, 2018).
    d. single herbicides (Kudsk, 1989)
    e. 2-4-way herbicide product tank-mixtures and accompanying, optimized, individual dose rates (Streibig et al., 1998)
    f. adding of adjuvants

Potentials of the DSS in Denmark have been calculated in terms of herbicide savings. These were found to be >40% in cereals and cultural grasses and >20% in row crops (mainly maize and sugar beet) in comparison with reference treatments (Rydahl, 2004; Jorgensen et al., 2007).

In Norway, Germany and Spain, results from field validation trials of 'IPMwise' and predecessor systems show that requirements for agronomical robustness have been met, while application of herbicides have been by 20-40% (like in Denmark), when using local best practice treatments as reference (Torresen et al., 2004; Sonderskov et al., 2015; Montull, 2016).

On the European level also alternative DSS for Integrated Weed Management (IWM) have been designed and evaluated. In an EU-survey assessing 70 DSS for IPM, of which 9 included facilities for IWM, it was concluded, that ‘IPMwise’ and predecessor DSS were the relatively most potent and the most widely used DSS for IWM in Europe (Been et al., 2009). Outside Europe different approaches have been used to design DSS for IWM, e.g. ‘RIM’ in Australia (Panell, 2000) and ‘HADSS’ in USA (Scott et al., 2001). However, neither of these have demonstrated herbicide saving potentials nor generic qualities on level with ‘IPMwise’ and predecessor DSS.

In Denmark, ‘IPMwise’ and a predecessor DSS, include >30 crops, 105 weed species and full assortments of herbicides, adjuvants and their generic alternatives, and recently also a few recommendations for non-chem (so far only mechanical) control, have been integrated. These 2 DSS constitute generally adopted points of references in Denmark among farmers, advisors and representatives from agro-chem companies as documented by user statistics.

The potentials in ‘IPMwise’ for reducing the use of herbicides arise from a systematic exploitation, of mainly the following conditions (Rydahl & Bojer, 2016):

- weeds are unevenly distributed in time and space
- complete weed kill is never required
- some weed species can be controlled sufficiently by down to about 10% of a registered herbicide dose rate

However, these potentials are still far from being fully exploited, and this challenge has been thoroughly investigated in sociological studies. A major and serious obstacle was found to be farmers' reluctance against manual weed scouting (Jorgensen et al., 2007). For logistic reasons, scouting must be executed by farm employees, but even up to 100% taxation on some herbicide products in Denmark, has not yet established a 'game-changer' effect.

In a Danish project with the acronym name 'RoboWeedMaPS' (2017-2020), the challenge of field scouting is addressed by use of manual/automatic analyses of weed infestations detected in pictures (Dyrmann, 2017; Dyrmann et al., 2018) and structured as required by ‘IPMwise’. This includes determination of weed infestations in terms of: weed species, weed growth stages (Teimouri et al. 2018) and counting of weed density. Initial results from automatic feeding of results from automatic determination of weed infestations to ‘IPMwise’ has been obtained on the entire-field level (Rydahl et al., 2017; I-GIS, 2018).

The aim of this work is to demonstrate potential herbicide savings, when combining dense image sampling with ‘IPMwise’, modified to create spatially uptimised multi-herbicide prescriptions, which are finally converted to grid based multi-layer herbicide dose-application maps.

This paper presents initial results from 1 Danish field in 1 year.

Methods

Until now, a relatively high number of pictures have been processed and used for training the convolutional neural network, but for a wider use a substantial number of combinations of weed species and classes of weed growth stage still need to be annotated to enable complete automatic determination of weeds (Dyrmann & Jorgensen, 2015; Dyrmann et al., 2016).

In most cases weeds could be determined automatically on a plant species level, and in some cases on a plant group level, e.g. some Danish ‘crucifer-’ and ‘grassy’ species. Instead of discarding the group level identifications, the information is used to find worst case representatives of common weed species within the groups to ensure sufficient agronomical robustness control in terms of efficacy targets, capable herbicide products, and related cost/environmental index.

A farmer’s field of 8.92 ha grown with winter wheat in Funen, Denmark, was recorded by a machine vision camera with a flash mounted on an ATV (described as Field A described by Laursen *et al.* (2017)). In the autumn of 2016, one photo covering 0.25 m^2 was taken for each approximately 10 x 10 m. In total, 862 photos were taken.

All photos were annotated by advisors and researchers using the online tool, ‘RoboWeedMaPS’ (I-GIS, 2018), to identify picture ‘thumbnails’ with single weed plants, and to determine the species and the class of weed growth stage. This manual annotation was combined with an automatic annotation by a trained convolutional neural network algorithm, which had previously been trained by use of results from manually annotated photos from many fields.

Most weed plants could be identified to species level, and some of the plants could be identified belonging to a group. E.g. monocotyledons could be identified to belong to the group, grasses (EPPO-code, 1GRAF). Also, certain dicotyledons like Tripleurospermum spp. (EPPO-code, 1COMF) (EPPO, 2018) could only be identified to the group level.

The farmer was asked to supply the names of identified grass species and relevant dicotyledons from the previous year, under the assumption that the composition of main species would not change within one year. The classes of weed size of all weed plants were determined automatically by the convoluted network.

The dataset with identified species, weed groups and classes of weed sizes was then analyzed to find the count of plants belonging to a species or group in each photo resulting in an exact density for the weed species/group. The groups were also mapped to the farmer supplied species, i.e. in cases where grasses were found, they were all interpreted as Italian Ryegrass as supplied by the farmer.

When weeds have 5 - 8 leaves and above, it is generally difficult to find capable herbicides for initial control in the autumn. To ensure that 'IPMwise' would find useful herbicides in most of the field, all weed sizes were therefore downsized to a maximum of 3 - 4 leaves, but only for the entire field. The actual weed sizes were still used in the processing on a plot level. The consequence of this is that 'IPMwise' would find recommendations for a majority of grids and no recommendations in only a few.

The analyzed dataset was fed to 'IPMwise' to automatically find a selection of herbicides for the entire field and optimal doses of these herbicides for each grid sample. According to the threshold model in 'IPMwise', some grid samples would require control, while other grids would not. Likewise, some grids would only require one herbicide, while other grids required 2-3 in tank-mixture. The herbicide dose would also vary grid by grid, as the weed density and weed size were different and thus required different herbicide amount and control levels.

The result was post processed to give various alternative cases of output with simpler dose recommendations, including on/off spraying strategy i.e. for simpler spraying equipment, where only 1 dose of each herbicide product could be applied. In this dataset, the herbicide doses in the grids were set to the maximum required dose for the field (worst case), but still the doses could be zero for one or all herbicides.

In economical calculations, amounts in Danish Crowns (DKK) have been exchanged into USD using and exchange rate of 628 DKK for 100 USD.

Weed maps

Based on the each of the collected image positions and the associated weed identification, classification, and counting weed maps for each weed species or group were estimated by use of inverse distance interpolation.

Transforming herbicide applications points to 4 herbicide application cases

Site-specific herbicide applications will be calculated for the Funen field are presented in 4 cases, which are:

1. The actual herbicide treatment applied by the farmer in the entire field
2. Treatment of the entire field with one single treatment according to a worst-case situation, as calculated by 'IPMwise'
3. On/off spot application map using fixed herbicide dose rates, as calculated by 'IPMwise'
4. On/off spot application map using varying herbicide dose rates, as calculated by 'IPMwise'

The interpolated weed maps are not used to generate the herbicide application maps for the sprayer. Instead, for each image, 'IPMwise' produce an application recommendation with regards to herbicide and application rate for case 3 and case 4, respectively, where the following procedures have been used:

- case 3:
  - Grid cells are set to 1 x 1 meter to get as many details as possible.
  - Inverse distance with
    - a 5 m search radius and weighting factor 1.
    - a 5 m view radius has been selected when the motorcycle makes a measurement point for every 10 m.
  - Items with no weed measurement are set to be ignored, giving a sharper grazing between the areas to be treated and where there is no treatment to take place.
  - The scale starts from 0 and consists of 2 levels (On / Off)
  - In order ensure engagement of the on/off section control in the Topcon X35 terminal the grid-based application maps are converted to polygons. Hence only one herbicide can be applied at the time.
- case 4:

- Grid cells are set to 5 x 5 m to get as many details as possible
- inverse distance with a search radius of 10 meters and a weighting factor of 2 has been chosen.
- A search radius of 10 meters has been selected to make sure it is possible to interpolate with the nearest measurement points as there are approximately 10 m between the measurement points.
- The weighting factor is set to 2 to get a smooth transition between 2 or more measurement points.
- The option of leaving measurement points with no measurement included in the interpolation. The scale starts from 0 and there may be unlimited number of levels.

Shapefiles generated for case 3 and case 4 were imported into Topcon X35 terminal controlling an injection based Danfoil sprayer (Danfoil, 2018).

Results

In Table 1, summary results from automatic determination of weed infestation in one winter wheat field located on the Danish island Funen, with an area of 8.92 ha, where 862 pictures were taken and automatically analyzed. A total of 22,448 images of single plants were extracted from the main pictures and classified as weeds, distributed among 11 weed species, where the 2 dominating classes of weed sizes were 2 and 4 leaves respectively, when counting both cotyledon- and true leaves (Table 1).

Table 1

Summary results from automatic determination of weed infestation in one winter wheat field on Funen, 2016.

Auto identified EPPO-code (group)	'IPMwise'ID, species or group level	EPPO-code, selected for IPMwise[1)]	Count of Thumbnails	2 most abundant number of leaves [2)]
1CRUF	BRASS	BRANA	9,990	2 and 4
CAPBP	CAPBP	CAPBP	84	2 and 4
CHEAL	CHEAL	CHEAL	40	2 and 4
GAETE	GAETE	GAETE	20	2 and 4
GERMO	GERMO	GERMO	4	3 and N/A
LAMSS	LAMSS	LAMSS	56	3 and N/A
1GRAF	MONOC	LOLMU	1,796	2 and 4
1COMF	MATSS	MATIN	2,540	2 and 4
1POLF	POLSS	POLCO	4	2 and N/A
STEME	STEME	STEME	1,012	2 and 4
1PLAF	VERSS	VERPE	1,072	2 and 4
VIOAR	VIOAR	VIOAR	4,640	2 and 4
Total			**22,448**	

Notes:

[1)] Weed name selected for 'IPMwise' to represent the EPPO-group, for calculation of efficacy targets, for selection of candidate herbicide products and for cost-optimization of accompanying herbicide dose rates. [2)] Total number of cotyledon- and true leaves.

Weed maps

Each of the 22,448 weeds is associated with a GPS coordinate, which enables the creation of a weed maps by species. Figure 1 shows the distribution of each weed species. The maps are generated using an inverse distance map of detected weed instances within 50 meters.

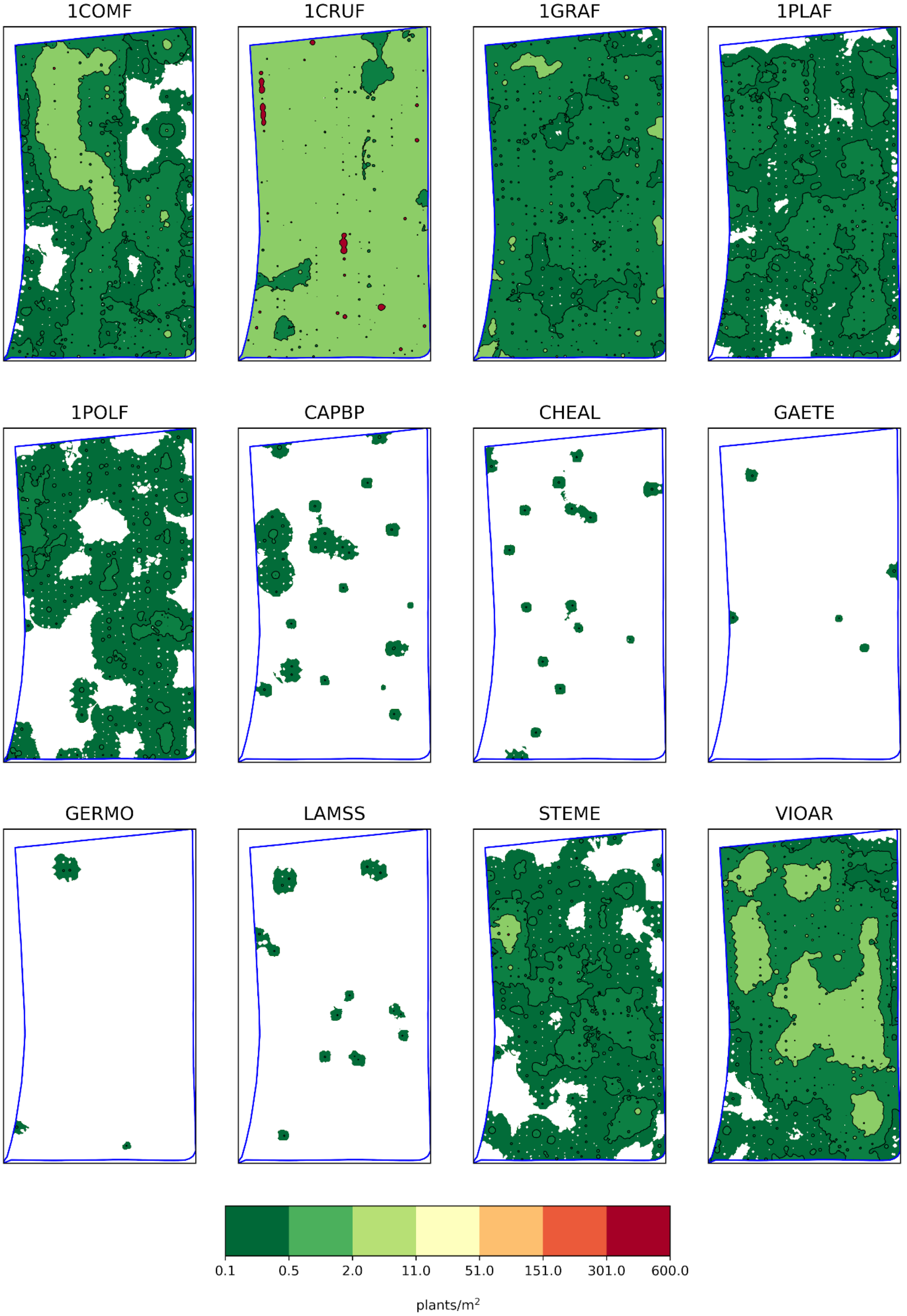

Figure 1
Weed distribution map for each of the detected species. White areas indicate less than 0.1plants/m^2

In Table 2, selected herbicide products and dose rates for the 4 cases are presented.

Table 2
Tank-mixtures for weed control comparing a farmer's actual application and recommendations from IPMwise in the same field and same year

No.	Case (decision maker)	Herbicides [1]	Unit	USD /unit	Max dose /ha	Avg dose /ha	Total cost USD /ha	Saved %	TFI /ha	Saved %
1	Farmer, entire field	DFF Lexus 50 WG Boxer	l g l	77.23 1.27 30.25	0.150 10.000 4.000	0.050 5.000 0.750	32.96	0	0.71	0
2	IPMwise, entire field	DFF Lexus 50 WG Atlantis OD	l g l	77.23 1.27 54.14	0.150 10.000 0,750	0.042 5.900 0.750	51.43	-56	1.34	-92
3	IPMwise, on/off spots fixed dose	DFF Lexus 50 WG Atlantis OD	l g l	77.23 1.27 54.14	0.150 10.000 0.750	0.009 2.150 0.516	31.37	5	0.73	-3
4	IPMwise, on/off spots, var. dose	DFF Lexus 50 WG Atlantis OD	l g l	77.23 1.27 54.14	0.150 10.000 0.750	0.006 1.730 0.322	20.06	39	0.75	-6

Note [1]

- DFF: 500 g/l diflufenican, 1 TFI = 0,2 l/ha
- Lexus 50 WG: 500 g/kg flupyrsulfuron-methyl-Na, 1 TFI = 20,0 g/ha
- Boxer: 800 g/l prosulfocarb, 1 TFI = 3,5 l/ha
- Atlantis OD: 2 g/l iodosulfuron-methyl-Na + 10 g/l mesosulfuron-methyl, 1 TFI = 0,9 l/ha

Table 2 shows that the farmer's choice (case 1) cost less than the cost optimized recommendation from 'IPMwise', which meet efficacy targets for the entire field, when using the dominating weed growth stages as shown in Table 1. Table 2 also shows that the cost of herbicides decreased, when moving from whole-field use (case 2) to the more spatially precise applications (cases 3 and 4), while the TFI was only slightly affected.

The efficacies of case 1 were not measured after herbicide application, and the recommendations for control in case 2 - 4 were not tested in practice. Instead, a reverse calculation was done using the farmers herbicides and doses (case 1) to find the expected efficacies on the auto recorded weed species. A similar reverse calculation with 'IPMwise' was done for the recommendations in case 2 - 4 to compare the expected effects of case 1 and case 2 - 4. The results are presented in Table 3.

According to 'IPMwise', only 5 of the 12 detected weed species needed to be controlled > 0% (threshold value), where efficacy targets varied from 84% against VIOAR to 96% against LOLMU.

In Table 3, efficacy targets on the weed species level as determined by 'IPMwise' are compared to achieved efficacies from the reference treatment selected by the farmer (case 1) and the cost-optimized treatment selected by 'IPMwise' (case 2).

Table 4 presents results of a special exercise, where the expected efficacies from the farmer's tank-mixture (case 1) in Table 3 have been re-entered in 'IPMwise' as new efficacy targets on the weed species level. If the farmer was satisfied with the obtained effects of his mixture at the time of application, 'IPMwise' can show what could alternatively be recommended by cost-optimization, to meet those effects.

The results show a cost reduction by 'IPMwise' for the entire field of 59% (case 2), 55% for on/off in spots (case 3) and 77% at variable dose rates (case 4).

Table 3
Efficacy targets and expected efficacies on weeds by EPPO-code names according to 'IPMwise'.

Weed name EPPO-codes	Efficacy targets in 'IPMwise' %	Case 1 Treatment by farmer, entire field, expected effects by 'IPMwise' %	Case 2 Treatment by 'IPMwise', entire field, expected effects by 'IPMwise' %
BRANA	90	57	90
CAPBP	0	94	97
CHEAL	0	0	0
GALSS	0	24	12
GERMO	0	80	80
LAMSS	0	42	82
LOLMU	96	24	92
MATIN	86	91	95
POLCO	0	3	1
STEME	87	86	98
VERPE	0	43	65
VIOAR	84	72	77

Note: in cells marked in red colour, efficacy targets as in 'IPMwise' have not been met.

Table 4
'IPMwise' recommendations based on target efficacies taken from expected weed effects of the farmers choice (case 1)

No.	Case	Herbicides [1]	Unit	USD /unit	Max dose /ha	Avg dose /ha	Total cost USD /ha	Saved %	TFI /ha	Saved %
1	Farmer, entire field	DFF Lexus 50 WG Boxer	l g l	77.23 1.27 190	0.150 10.000 4.000	0.050 5.000 0.750	32.96	0	0.71	0
2	'IPMwise', entire field	DFF Lexus 50 WG	l g	77.23 1.27	0.150 10.000	0.042 5.900	13.38	59	0.51	28
3	'IPMwise', on/off spots, fixed dose	DFF Lexus 50 WG	l g	77.23 1.27	0.150 10.000	0.009 3.306	13.81	55	0.22	69
4	'IPMwise', on/off spots, var. dose	DFF Lexus 50 WG	L G	77.23 1.27	0.150 10.000	0.006 2.693	7.48	77	0.26	63

Note [1]

- DFF: 500 g/l diflufenican, 1 TFI = 0,20 l/ha
- Lexus 50 WG: 500 g/kg flupyrsulfuron-methyl-Na, 1 TFI = 20 g/ha
- Boxer: 800 g/l prosulfocarb, 1 TFI = 3,5 l/ha

Herbicide application maps

The application maps imported into the Topcon X35 terminal with the sprayer simulator engaged for case 3, the on/off application, using the Danfoil section control is illustrated in Figure 2.

Figure 2
The on/off application map for the DFF herbicide case 3 imported into the Topcon X35 terminal

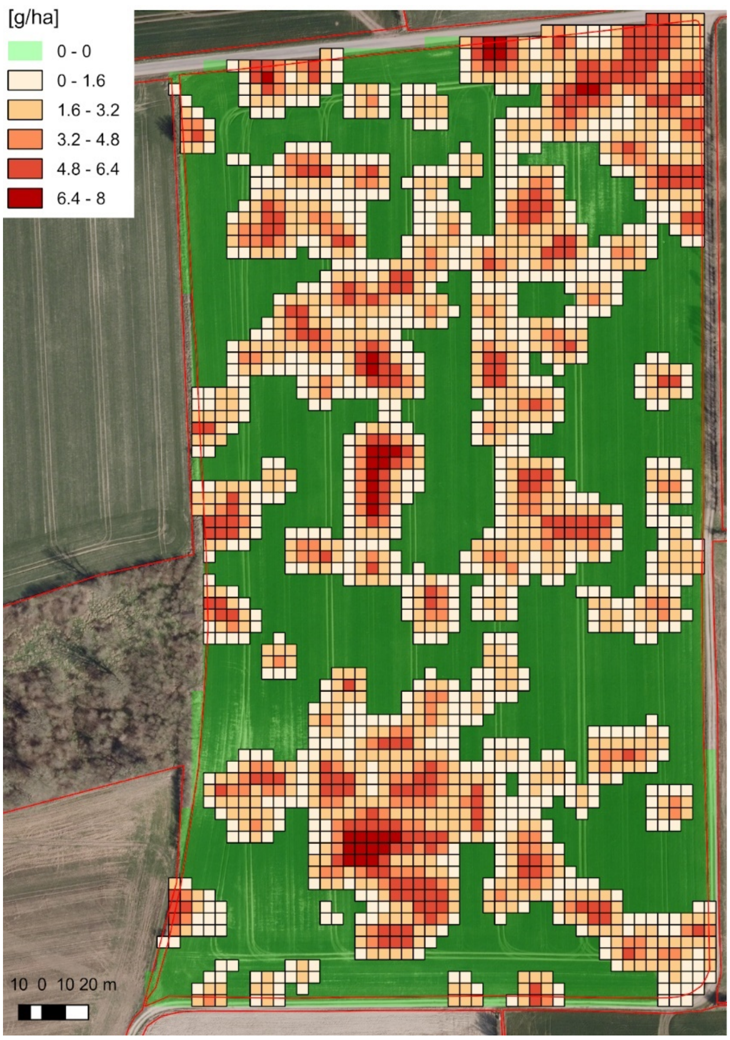

Figure 3
The variable Lexus 50 WG shapefile for case 4 to be imported in the sprayer terminal

In Figure 3 the shapefile for one of the herbicides is illustrated indicating a significant variation in the 'IPMwise' spatially variable dosing indicating a significant herbicide reduction assuming the spray controller and the sprayer on hand can fulfill this.

In Figure 4, the variable herbicide application for one of the two herbicides is illustrated.

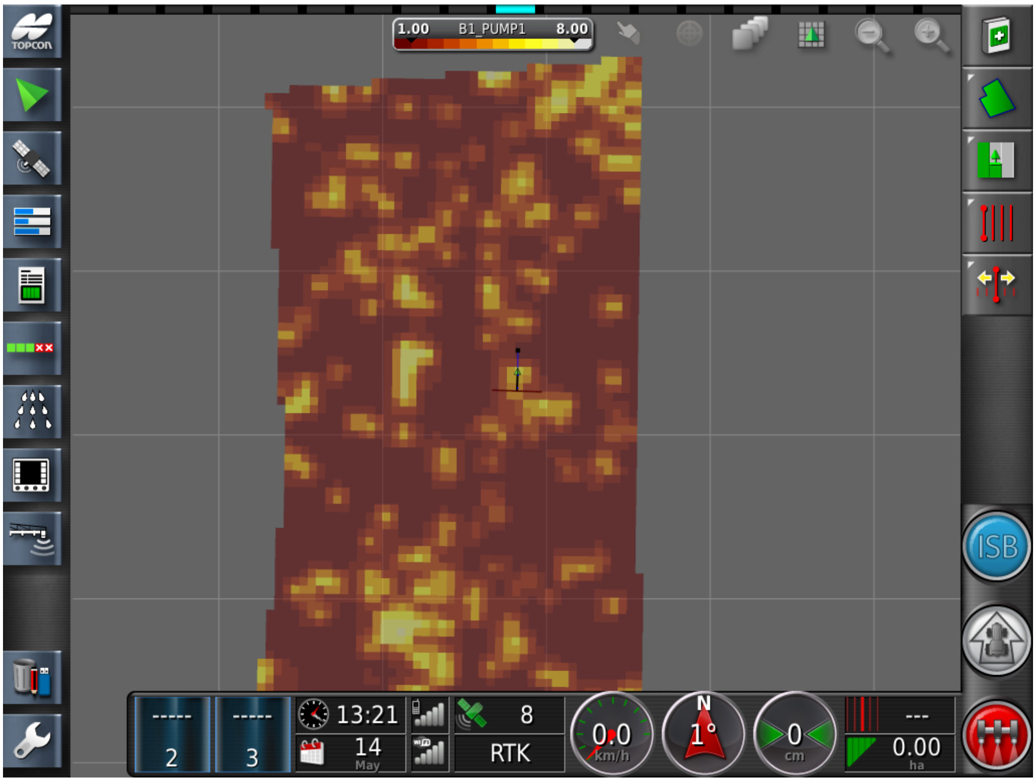

Figure 4
The variable Lexus 50 WG shapefile for case 4 imported into the Topcon X35 terminal

Discussion

In Table 2, the systematic downsizing used, from the worst-case sizes of weeds being 5-8 leaves to 3-4 leaves, are supported by the results in Table 1, which show the sizes of the two most abundant classes of weed size for the five weed species, where control was required, which were 2-4 true leaves.

Table 2 shows that in contrast to results from massive field validation grid trials with 'IPMwise' and predecessor systems (Rydahl, 2004; Jorgensen et al., 2007), the 'IPMwise' solution for the entire field (case 2) was found to be more expensive than the farmer's choice (case 1). In fact, the farmers reasonings for making this decision, are not known. However, when looking into the details of the farmer's choice, it turned out that this treatment could not be expected to meet all the efficacy targets bigger than 0% as determined by 'IPMwise'. This was the case for BRANA, LOLMU and VIOAR (Table 3).

Also cost-optimized recommendation from 'IPMwise' for treatment (case 2) did not meet the efficacy target against LOLMU and VIOAR, while the efficacy targets >0% all other weeds were met. Against LOLMU, the efficacy target was determined by 'IPMwise' to be 96%, while the predicted efficacy from the cost-optimized treatment was 92%. Against VIOAR the efficacy target was 84%, while the predicted efficacy from the cost-optimized treatment was 77%.

These discrepancies arise, because 'IPMwise' used worst-case classes among the reported classes of weed size, to calculate expected efficacies, which in the case of LOLMU and VIOAR were 5-8 leaves, while the 4-leaf stage of LOLMU and VIOAR, were used to find a cost-optimized recommendation for treatment. This mismatch is currently being investigated furtherly, which the aim of solving.

When considering 'IPMwise'' underlying herbicide dose-response models and the asymptotic characteristics of these, when approaching 100% weed kill, worst-case cases may be considered as unbalanced in terms of herbicide input and cost, as compared to solutions, where a relatively smaller proportion of spots may be left slightly unsatisfactorily controlled (Rydahl and Bøjer, 2016). Consequently, alternative options to report weeds for an entire field are currently being considered, e.g. fractiles and averages of both weed density classes and weed growth stage to avoid such unbalances and substantial overkill.

The herbicide doses in Table 2 (case 2) are results from optimizing the composition of herbicides (in tank mixture) and dose rates, to the weed composition, maximum densities and classes of weed size of the weeds in the entire field. The increased savings by moving from case 2 to 3 results from tailoring the composition of herbicides and dose rates to the weeds in the points, and the strategy for instantly turning herbicides on and off. The further saving in case 4 results from the global varying dose tailored to the identified weeds, densities and weed sizes as well as the option to turn one or more herbicides on and off individually in the points. In case 4, however, lag-times and -distances to change a dose rate on the sprayer have not yet been considered.

Currently, exercises are made for technical integration with a 'Multi Dose Injection Sprayer system (Danfoil, 2018), which is a so-called 'air-sprayer', which use relatively low water volumes as compared to hydraulic sprayers. This sprayer has been mounted with 5 parallel booms, 5 small tanks for concentrated herbicide and a big tank for water and an interface to link up to an electronic herbicide application map provided in collaboration by 'IPMwise' (Boejer & Rydahl, 2016) and Naesgaard Mark (Datalogisk, 2018).

Table 4 shows that potentials for reducing cost increases furtherly, when the expected efficacy from the farmer's choice, is used for a re-cost-optimization. This exercise was made to obtain an alternative calculation of potentials for reducing the cost, however, such drastic reductions in the expected efficacy, especially on LOLMU, which is known to cause serious yield losses even in moderate infestations, must be considered more as theoretical exercise than a real potential, due to the risk of yield loss.

A limitation of the current Topcon X35 controller, which is shown in Figure 4, is that it is only reading the point on the map, where it expects the GPS antenna to pass over in a preset time offset. This is not optimal since the spatial herbicide application rate should consider the full width the sprayer boom will be passing over. Furthermore, mixing delays for the specific sprayer system should be incorporated in future sprayer controllers.

To put the achieved cost-reductions in this paper in perspective, initially it should be considered, how the spatial resolution in decision making and application of measures for weed control has developed gradually over time. Still in the 1990ies, national recommendations on the crop level for weed control were used in some countries. In some cases, such recommendations were even compulsory. In some EU countries, national laws are currently being revised to allow recommendation of dose rates, which are not stated on product labels (Rydahl, 2018), but which are required to comply to IPM-principles as in EU Directive 2009/128/EC (European Parliament, 2009).

In other EU countries, extension services, which operate on the regional level, provide recommendations on how to properly control weeds. Using the so-called Treatment Frequency Index (TFI) as a reference for measuring the total input of herbicides, it was concluded that such "national use" in some East-European countries in the 00ies had minimum 100% higher TFI as compared to recommendations from Danish regional advisory services in similar crops, weed infestations and climates (Rydahl, 2018).

The results from field validation tests of 'IPMwise' and predecessor DSS for weed control on the field level, documents opportunities and potentials in precision weed control, by increasing the spatial resolution from the regional to the field- and furtherly to the sub-field level, where the latter is sometimes also referred to as the 'site-specific' level. Potentials for reducing use of herbicides, when changing from the regional- to the field level, have been found to be 20-40% in terms of cost, in different Danish, Norwegian, German and Spanish crops (Sonderskov et al., 2014, Torresen et al., 2004, Sonderskov et al., 2015 Montull, 2016).

The provisional results in this paper from a Danish field on the island of Funen field with winter wheat in one year, provide some initial indications of the potential of transferring decision making from the field to the sub-field level - in this case to a 10 x 10 m grid. When using the farmer's somewhat unsatisfactory treatment in terms of expected efficacy as a reference (case 1), a 39% cost saving was achieved.

In case the farmer's choice (which have unsatisfactory low efficacy), is replaced by the cost-optimized recommendation from 'IPMwise' for this entire field as an alternative reference, cost savings amounted to (51.43 USD/ha - 20.06 USD/ha) / 51.43 USD/ha * 100% = 61,0%, according to figures extracted from Table 2. When using instead current Danish 'best practice' treatments on the regional level as a reference, cost savings increases to: 40% (from region to field) (Jorgensen et al., 2007) + 40% (from region to field) * 61% (from field- to site-specific level in this single field) = 64.4%.

An ultimate spatially precise weed control may be achieved when single weed plants are evaluated and controlled separately. In semi-field studies, which had >100 weed seedlings/m^2, sufficient weed control was achieved by placing droplets of glyphosate-solutions to single weed seedlings, in a dose rate equal to 1 gai glyphosate/ha (Graglia, 2004). Compared to the recommended dose of glyphosate for control of weed seedlings, which in Denmark is 720 gai/ha, this reduction of cost or TFI equals to (720 g/ha -1 g/ha)/720 g/ha * 100% = 99.86%.

Conclusion

In this paper, results from 862 photos taken in a 10 x 10 m grid, show that 22,448 thumbnail pictures of single weed plants were detected. Results from automatic analyzes by a trained convolutional neural network showed that these pictures included 12 weed species with mainly 2-4 (true) leaves, of which 5 occurred in densities requiring control, according to the DSS named ‘IPMwise’.

When using cost-optimization as provided by ‘IPMwise’ for the entire field as a reference, the cost, when applying herbicides in a 10 x 10 m grid and re-cost-optimized by ‘IPMwise’, was reduced by 61%, while the potential was only 39% when using the farmers’ choice as reference, which, however, turned out to provide too low efficacy on 2 quite noxious weed species, as compared to efficacy targets used in ‘IPMwise’.

However, while this paper deals with techniques and potentials, when moving from field- to site-specific treatments, it is also interesting to consider techniques and potentials, maybe as an initial step, when moving a logical first step, namely from regional to field-specific treatments. This step has been thoroughly researched in Denmark (Jorgensen et al., 2007). When using recommendations on the regional level as a reference, the total potential of moving to field- and site-specific decision making and treatments with herbicides was found in one field to be 64.4%.

The step of moving decision making and application of herbicides from the regional to the field level, has also been intensively studied on the European level, where a reduction potential of 20-40% has been documented from use of ‘IPMwise’, when compared to local ‘best practice’ recommendations (Sonderskov et al., 2014; Montull, 2016; Torresen et al., 2004; Sonderskov et al., 2015).

These potentials for reducing the use of herbicides have been known for decades, and in Denmark, farmer’s aversions against manual field scouting have been found to constitute a dominating single obstacle for a wider exploitation of these potentials (Jorgensen et al., 2007).

Consequently, the progress presented in this paper on: 1) automatic determination of weed infestation as in ‘RoboWeedMaPS (I-GIS, 2018)’, 2) technical integration with ‘IPMwise’ (Bojer & Rydahl, 2016), 3) technical integration with ‘Naesgaard Mark’ (Datalogisk, 2018) and 4) technical integration with the ‘Multidose Injection Sprayer’ (Danfoil, 2018), is expected to poses a potential to remove an old, well-known bottleneck against manual weed scouting and thereby establish a new game-changer effect.

Additional R&D is required, planned and in progress to additionally improve the reliability of automatic weed recognition, to expand the number of identifiable weed species and to furtherly consolidate determination of larger weed sizes. Another current challenge is find new solutions, where the state-of-art in lag-time and -distances on sprayer equipment, will be dealt with in order to establish a more useful, coherent and potent techniques.

As both the DSS and the algorithms for automatic determination of weed infestations, have demonstrated generic qualities, worldwide opportunities are expected for scaling up and out. This may include also design of new commercial products and connected business models.

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