The International Society of Precision Agriculture presents the

15th International Conference on Precision Agriculture

26–29 JUNE 2022

Minneapolis Marriott City Center | Minneapolis, Minnesota USA

Economic potential of RoboWeedMaps - use of machine learning for production of weed maps and herbicide application maps

Per Rydahl and Ole M Bojer, IPM Consult ApS, Denmark
Niels-Peter Jensen, Morten Back-Nielsen and Laura-Carlota Paz, I-GIS A/S, Denmark
Birger Hartmann and Per Andersen, Datalogisk A/S, Denmark
Rasmus Joergensen, AgroIntelli A/S, Denmark
Martin Soerensen, Danfoil A/S, Denmark

A paper from the Proceedings of the
15th International Conference on Precision Agriculture
June 26-29, 2022
Minneapolis, Minnesota, United States

Abstract.

In Denmark, a new IPM 'product chain' has been constructed, which starts with systematic photographing of fields and ends up with field- or site-specific herbicide application.

A special high-speed camera, mounted on an ATV took sufficiently good pictures of small weed plants, while driving 30-40 km/h. Pictures were uploaded to the RoboWeedMaps (RWM) online platform, where persons with agro-botanical experience executed 'virtual field inspection' (VFI) in the pictures to determine weed species and classes of weed size.

These determinations served 2 purposes:

- *As input to 'IPMwise', which 1) evaluated needs for control and 2) identified cost-minimized options for herbicide application*
- *Training of 'machine learning' (ML) to enable automatic discriminations of weed species and growth stages*

In 2017-2021, around 400 pictures/ha were taken in 84 Danish fields grown with cereals and maize, and 76 trainings of ML were executed. Around 80 ha/day were photographed, which out-competed photographing by drones.

Currently, the following object in pictures can be auto discriminated by use of ML, with sufficient agronomical robustness: 1) irrelevant objects such as soil, stones, dead plant material, etc., 2) crop plants, yet: cereals, silage maize and oilseed rape, 3) weed plants, yet: monocots and dicots *plus additional discrimination of Cirsium arvense.*

The results from VFIs in the 84 fields were entered in 'IPMwise', which returned cost-minimized and -sorted options for control. By use of the farmer's planned/executed whole-field treatments as references, a theoretical economic potential of 52-73% reduction of herbicide input was found in different cereal crops, equal to averagely 35 USD/ha. In maize, additional photographing and analyses are required to estimate potentials.

On top of herbicide savings arising from field-specific herbicide application as quantified above, an additional potential arises from a spatially more precise weed control, in terms of site-specific control. Until now this has been enabled and demonstrated for 1 dicot species, Cirsium arvense.

This species was identified in 13 of the 84 photographed fields, where additionally 88% reductio was measured by leaving patches untreated, which had 4 or less plants/m2. The RWM platform delivered weed maps, while IPMwise integrated with an online Farm management system (FMS) 'Naesgaard Mark', deliverered recommendations for whole-field- or site-specific treatments, as preferred by the farmer. In case of site-specific application electronic treatment files readable to the Danish Danfoil sprayer system and other brands of 'spray-controllers' will be provided.

Both the RWM and 'IPMwise' systems have both demonstrated generic qualities suitable for scaling.

Keywords.
decision support system, integrated weed management, IPMwise, machine learning, weed infestation, site-specific

Introduction

In Denmark, targeted R&D since 1989 has led to commercial 'Decision Support Systems' (DSS), which can assist decision making on farm and field levels on control of weeds, pests and diseases. This work was sponsored by public Danish and EU funding since then. This work included also field validation experiments with these DSS, to document both agronomic robustness and possible both economic and environmental benefits, as compared to existing 'best practice' recommendations for control, as provided by crop advisors.

'IPMwise' is one such DSS, specialized for weed control (Rydahl and Bojer, 2016), which is now a 4th generation tool in terms of IT basis and agronomic features for weed control. IPMwise intends to exploit that:

- Weeds are unevenly distributed in time and space
- Weeds differ in terms of needs for control under various conditions
- Weeds differ in susceptibility to herbicides under various conditions

Accordingly, when using a field report on weed infestation (combinations of weed species and classes of weed growth stages and -density), IPMwise evaluates needs for control and identifies accompanying options for control. IPMwise provides a list of options for control, which has been minimized and sorted according to preferences as provided by users, yet cost and 2 environmental index. Options for control include both single herbicides and 2-4 way tank-mixtures of herbicides. A few options for mechanical weed control have also been included, however, yet only for situations, where herbicides are sparse, less efficacious or more expensive, which are typically field with weeds in late growth stages.

IPMwise includes also additional tools, which can provide deeper insight in dose-response relations. This includes specific tool for 1) weed identification, which use botanical keys and pictures of single weed plants in various growth stages 2) presentation of expected efficacy of 1 herbicide product, 3) presentation of expected efficacy of specific tank-mixtures and dose rates as specified by the user 4) presentation of overview of expected efficacy of all available herbicides in a crop during a full growing season (autumn/spring). All such presentations will also be adjusted for classes of weed size, temperature, and drought stress.

In Denmark, IPMwise includes now 32 crops and full assortments of herbicides and weeds. In Norway 6 crops, in Germany 4 crops, in Spain 19 crops, which have all been equipped with full assortments of weeds and herbicides. In these 4 countries, IPMwise offers also 1) control of already herbicide resistant biotypes of weeds, and 2) measures to prevent/delay development of new herbicide resistance (Rydahl et al., 2022).

After completed field validation experiments, which documents sufficient levels of weed control and 27-60% reduction of input of herbicides, when using regions national 'best practise' treatments as references (Rydahl et al., 2022), IPMwise is currently recognized by national crop advisors, suppliers of herbicide products and farmers as a professional point of refence. As such field validation experiments were executed in different fields, this potential express potentials for field-specific use of IPMwise.

Despite the a.m. potential, a major obstacle has been identified for a wider implementation, in terms of needs for manual field scouting to identify weed infestations, as required by IPMwise (Jorgensen, 2007). In response, this paper provides a status on results from systematic photographing of fields, and training of 'machine learning' (ML) to auto determine weed infestations. This initiative aims for harvesting the potential mentioned above for field specific use of IPMwise, plus a yet only poorly examined, but expected additional potential for site-spefic application of herbicide.

In successful, this technology may become a game changer, for both field- and site-specific herbicide application. Simultaneously, weed control in fields may become more rational in terms of responses to actual needs for control, and in terms of offering new contributions to improve biodiversity. The latter by leaving spots untreated, which have sufficiently low weed infestations, which do not require control, according to parameterization of IPMwise.

In 2017-2020, The Danish Innovation Fund funded the 'RoboWeedMaps' (RWM) project, which designed and constructed a new 'product chain', which starts with photographing fields and ends up with field- or site-specific herbicide application. This paper provides a status on this work.

Methods

The RWM project included contributions from 3 faculties in Aarhus University, Denmark (engineering, agronomy, sociology) and 5 Danish companies, which supplied various products to support a new 'product chain' (Rydahl et al., 2017).

Initially, a dual high speed camera system was designed, constructed and mounted on an ATV. This 'RWM-camera', use a new and optimized combination of sensor, camera settings and flash, which can take sufficiently good pictures of small weed plants, while driving 30-40 km/h. The pictures were taken with a 5 Mpixel camera, covering ~ 0.25 m2 and in some cases 0.4 m2 of ground.

The RWM-camera system is shown in Fig 1, where se of pressured air around the lenses ensure clean lenses also in wet/dusty conditions. An online RWM-platform was designed and constructed, which can receive and manage uploads of huge amounts of geo-tagged pictures from fields, and deliver various field maps, which document both locations of fields and photographed spots, and various weed maps generated by use of interpolation.

Research in sampling strategies was designed and executed, to support identification of suitable sampling strategies, which sufficiently robust represent the spatial variability in weed infestations in Danish fields. (Somerville et al., 2019).

Research was also planned and executed in 'machine learning' (ML), aiming for auto identification of various objects on pictures. This included identification of weeds, where specific ML-training was executed by use of metadata from VFIs. Ideally, ML-trainings must include all the kinds of variabilities, which may also occur in actual varieties of fields. For example, different growth stages, rain droplets, dust, bites by animals, effects of extreme temperatures, overlapping with other objects, etc.

During execution of RWM-project, 76 ML trainings was executed (Dyrmann et al, 2016). This work is still ongoing aiming for additional auto discrimination on the weed species level, combined also with growth stages of these.

Fig 1 – ATV mounted with the RWM dual camera system, and additional components

After upload of pictures to the RWM online platform, virtual field inspections (VFIs) were executed in ML-identified and auto cut-out thumbnail pictures, which had been auto sorted in 2 groups - monocots and dicots. Results from ML also included calculation of weed densities, in terms of numbers/m2.

Thumbnails in these 2 groups were also auto sorted descending, according to weed size (Teimouri et al., 2018).

Upon this sorting, 4 samples each of 100 thumbnail pictures were selected for VFIs, where persons with weed botanical skills manually identified domination weed species and -growth stages, by use of systematic down-scrolls in thumbnail pictures to achieve representative samples. These counts were used as weights for distributing the auto counted mono- and dicot thumbnails into weed species, dominating growth stages and densities (plants/m^2), as required by IPMwise.

Results from such VFIs were used for 2 purposes 1) as metadata for additional ML-training and 2) as input to IPMwise to identify needs for control and accompanying options for control, which were sent back to the farmers, who had allowed photographing.

In case such auto discriminations can be made only on higher botanical levels, e.g. family and genus levels, IPMwise will auto select representatives of such groups on the weed species level, which can sufficiently robust represent such classifications. In this way the ‘product chain’ can be run, even on yet imperfect ML-discriminations, and simultaneously develop gradually from there. This method was particularly relevant for monocot, where only a few species can yet be determined by use of VFI and auto determination by ML.

Results

Based on results from investigations of sampling strategies (Somerville et al., 2019), an image distance of 5 to 10 m was selected. This results in around 400 images/ha, which with a sample size of 0.25 m2/image represents about 1% of a field. In a 25 ha field 400 pics/ha x 5 mB/pic x 25 ha = 50,000 mB = 50 gB, which requires good conditions for both transfer and analyses.

In the 84 photographed fields, the crops were spring barley (16 fields), 3 winter cereal crops (60 fields) and silage maize (8 fields). However, results from maize have been excluded from analyses, because only one time of photographing was executed, while minimum 2 times should have been executed, according to usual practices and reference treatments.

A total of 23 farms, 84 fields and 1,278 ha, representing most regions in Denmark, were photographed. In terms of capacity, approximately 70-80 ha was photographed during 8 hours, which included also time for logistic planning and shifts between fields. This capacity outcompetes photographing by use of drones, which was tested in the initial phase of the RWM project. In Fig 2, a field map is presented, where locations of photographs have been marked. In the RWM platform, the user can study single pictures taken in selected spots, to evaluate qualities.

Fig 2 – example of field map with boundary in red line and markings, where photographs have been taken in black dots.

In Fig 3 an example of 1 RWM-picture of 0.25 m^2 is shown.

Fig 3 – example of 1 RWM-picture representing 0.25 m^2 (here length has been additionally cut)

In Fig 4 the user-interface of the tool used for execution of VFI is presented. In this case dicot weeds have been selected (in Danish: '2-kimbladet') for VFI. Persons with suitable botanical skills executed VFI to identify both crop- and weed plants.

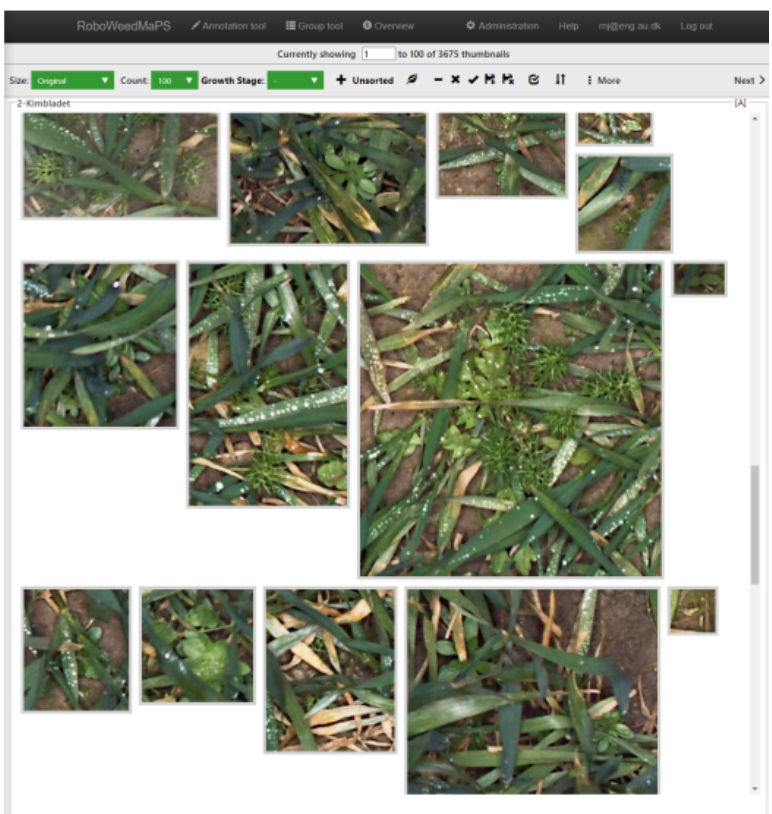

Fig 4 – user interface of tool for executing of VFI

For yet 1 dicot species, Cirsium arvense, Fig 5 shows results of auto discriminations executed by ML.

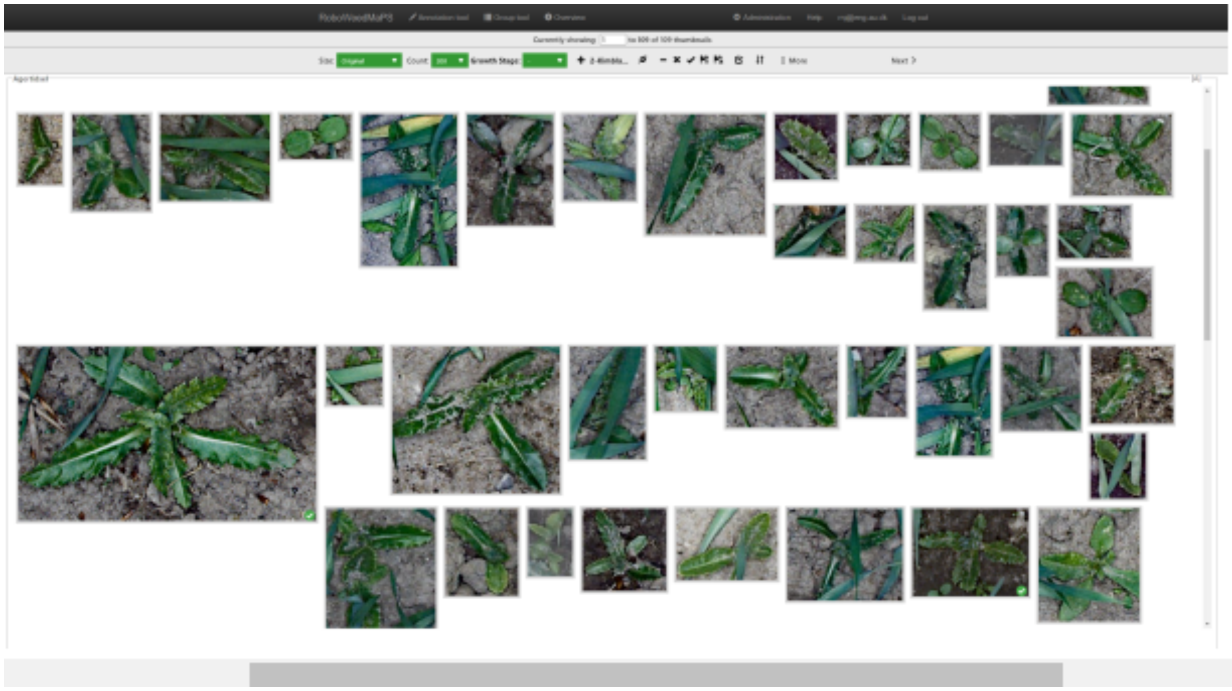

Fig 5 – Results from ML-discriminations of 1 weed species, Cirsium arvense

At the end of the RWM project in 2020, 76 ML trainings had been executed, and this is still an ongoing process, now run by a business case. Until 2020, approximately 250,000 pictures were collected, of which approximately 90,000 pictures were selected for ML-training.

Initially, ML-training was executed to identify irrelevant objects on pictures such as bare soil, stone, mosses, dead plant material, etc. Also crop plants yet cereals and maize can be auto discriminated. Approximately 900,000 auto framed weed objects were identified, which were also classified by ML as being monocot or dicot.

Additional discrimination and ML-reclassification of monocot into species is particularly difficult, because it is often necessary to study particularly botanical characteristics, which requires special focus and use of a magnifying glass. However, in Denmark, a particularly easily recognizable and at the same time very widespread monocot species by use of VFI is Poa annua, provided it has reached a minimum growth state.

For transfer to IPMwise, other 'indeterminate monocots', are hereafter considered to be Lolium perenne. This species was selected as a default representative, because it is one of the most difficult and expensive to control, and thus also an agronomic relatively safe representative, until ML can hopefully provide additional support in this domain.

In the 84 photographed fields, a total of 30 dicots and 1 monocot species were identified by VFI. In Fig 6, a weed map is presented for the same field as in Fig 2. In Fig 7, a treatment map is presented of the same field, for control of dicot, when using a threshold value of 4 plants/m2, which is equal to one plant in one picture, which represent 0.25 m^2 ground cover.

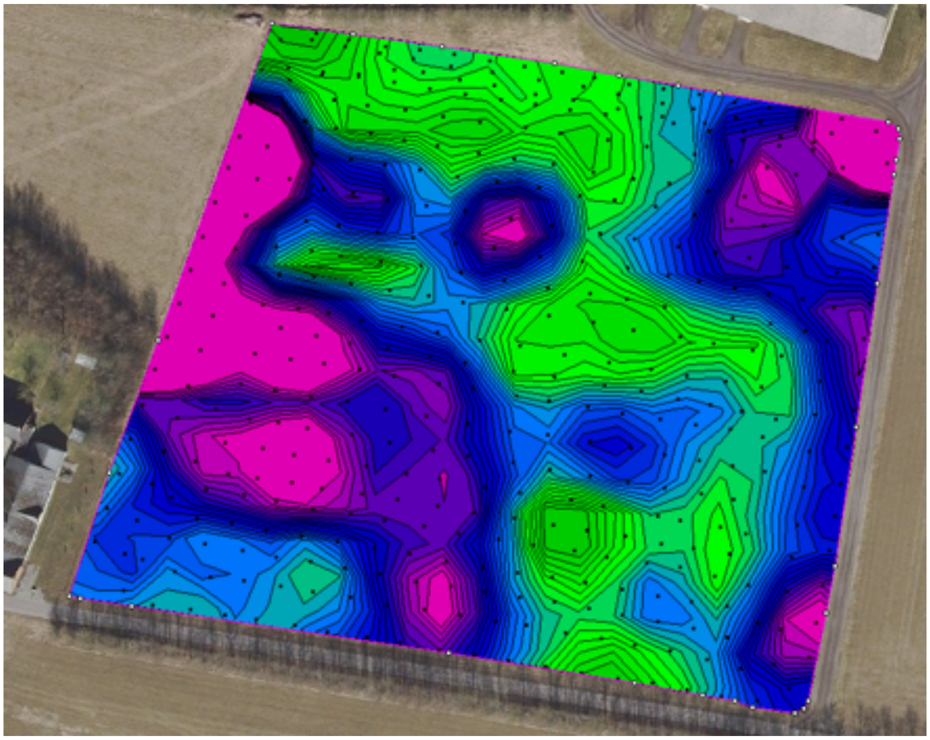

Fig 6 – weed map for dicot of the field in Fig 2, where green colors mean low density

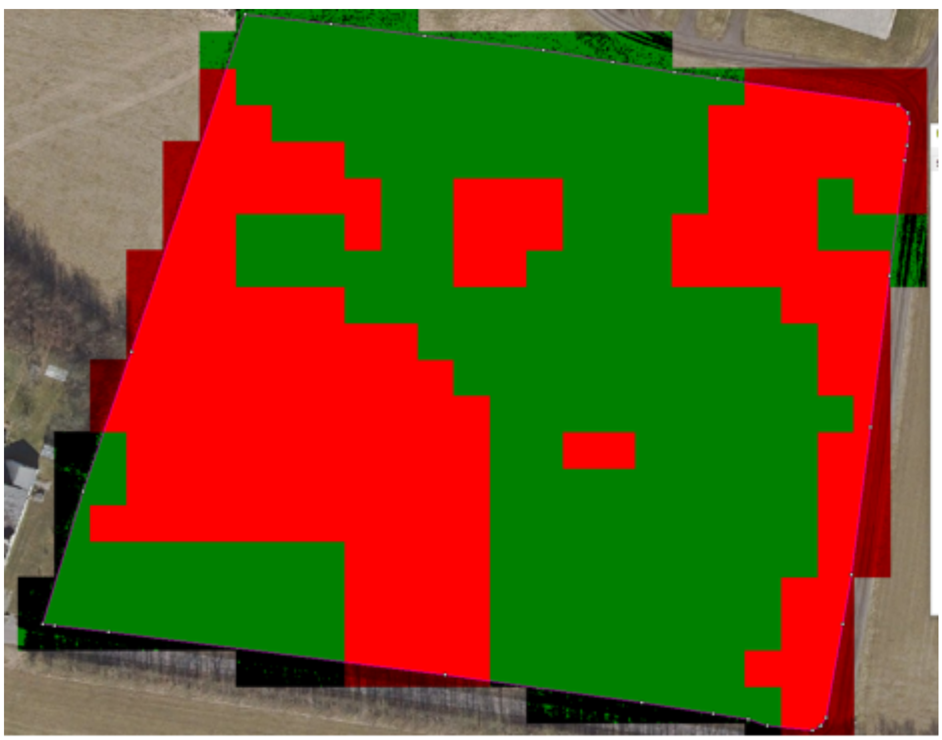

Fig 7 – treatment map against dicot of the field in Fig 2, by use of a threshold value of 4 plants/m^2, where areas marked in green color do not need control

In the 84 photographed fields, the involved farmers all provided access to the herbicide treatments, which they had already planned to use, and which were used as reference treatments to calculate economic potential from the RWM 'product chain'. In Tab 1, a summary results on economic potential are provided for each of the photographed crops.

Tab 1 – Summary of cost from reference treatments and from potential treatments in photographed fields (Petersen et al., 2021)

Crop	Season	No. of fields	Cost reference (USDha)	Saved cost, if farmer's choices on weed control had been replaced by cheapest option from RWM/IPMwise
Winter barley	Autumn	3	20	-401%
Winter barley	Spring	7	23	73%
Winter wheat	Autumn	21	41	52%
Winter wheat	Spring	21	36	76%
Winter rye	Spring	8	14	57%
Spring barley	Spring	16	42	72%
Sum		76		

In autumn treatments of winter barley, treatments identified by RWM/IPMwise were approximately 4 times as expensive as the farmers choices. This result was a consequence of the fact that only few and relative expensive herbicides are available in Danish winter barley, in autumn, for control of Lolium perenne, which was selected (in all crops) as a safe default representative of monocot. For the other cereal crops and seasons, the average % saved cost from uniform whole-field application varied from 52% to 73%.

For 1 weed species, which can yet be auto discriminated by ML, Cirsium arvense, which was found in 13 of the 84 photographed fields, additionally 88% reduction was achieved by leaving parts of these fields untreated, where less than 4 plants/m^2 (1 plant/photo) were found (Petersen et al., 2021).

Conclusion

After systematic photographing of 84 fields, a 'machine learning' (ML) system was trained 76 times to automatically identify elements on pictures, yet which can be auto-discriminated as 1) irrelevant objects such as soil, stone, dead plant material, etc. and 2) crop plants (yet cereals and maize) and 3) weeds yet in 2 classes, monocot and dicot.

In 84 photographed fields, where the crop was cereals and maize, the potential of the RWM-chain was compared to the farmer's already planned/executed treatments for uniform whole-field treatments. This showed average savings of 52-73% in different cereal crops, equal to 35 USD/ha, if uniform whole-field herbicide applications as provided by RWM/IPMwise had been used instead of the farmer's already planned treatments.

Provision results from site-specific control one dicot species, Cirsium arvense. This species propagates mainly by roots, and therefore often occurs in distinct patches. As this species were also found in 13 of the 84 photographed fields, this species was selected for initial exercises of producing site-specific weed- and treatment maps. These maps showed that in total, 88% of the areas did not have minimum 4 pl/m2 (1 plant/0.25 m2 photo) (Petersen et al., 2022), which is the threshold value used in IPMwise for this weed.

The identified potentials arising from both field- and site-specific herbicide application, arises mainly from a systematic exploitation of the following aspects 1) that weeds are not homogenously distributed in time and space 2) weed species differ strongly in need for control in different crops and conditions and 3) weed species differ strong in susceptibility to various herbicides and conditions.

Additional conditions which also affect the a.m. interactions are weed size, temperatures, drought stress and options for using multiple herbicide applications and tank-mixtures of different herbicide products. These conditions have all been integrated in the IPMwise system, which is a Decision support System (DSS) for Integrated Weed Management (IWM), which have customized for major crops, and fully validated in field trials, in now 4 European countries (Rydahl et al., 2022)

These theoretical results, are currently being supported by a series of full-scale field validation experiments, which are currently being executed.

In addition, IPMwise/RWM specifically addresses 7 of 8 general principles on 'Integrated Pest Management' (IPM), as specified in a EU directive (European Parliament, 2009). Specific results on potential for leaving parts of conventional fields unsprayed with herbicides, may be used to document also improvement of plant biodiversity, which is an increasingly important political issue in Europe.

Acknowledgements

Danish Environmental Protection Agency (Danish EPA), sponsored design and contruction of decision support systems for IPM (1989-)

EU framework programs sponsored EU collaborations on R&D relating to IPM and export of decision support systems for IPM (2001-)

The Danish Agricultural Agency sponsored the RoboWeedSupport project (2014-2016).

Danish Innovation Fund sponsored the RoboWeedMaPS project (2017-2020).

References

Dyrmann M, Karstoft J, Midtiby H, Skov H (2016). "Plant Species Classification Using Deep Convolutional Neural Network." Biosystems Engineering 151, 72–80.

European Parliament (2009). Establishing a framework for Community action to achieve the sustainable use of pesticides, Annex III

https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2009L0128:20091125:EN:HTML

Petersen KL, Jensen KL; Nielsen, Back, Morten; Paz, Laura-Carlota; Rydahl, Per; Bøjer, Ole M; Scovill, Alea; Jørgensen, Rasmus Nyholm; Laursen, Morten S.; (2021). Analysis of potential herbicide savings using experience and data from the RoboWeedMaPS project, 255 pp (with summary on page 3)

https://agrinavia.com/wp-content/uploads/2021/04/Analysis-potential-herbicide-savings.pdf

Rydahl P, Bojer OM, Torresen K, Montull JM, Taberner A, Buckmann, H, Verschwele A (2022). IPMwise – economic potential in 4 European countries of a generic decision support system for integrated weed management. Proceedings of the 15th International Conference on Precision Agriculture. June 26-29, 2022, Minneapolis, Minnesota, United States.

Rydahl P; Jensen NP; Dyrmann, M; Nielsen, PH; Joergensen, RN (2017). RoboWeedSupport - Presentation of a cloud based system bridging the gap between in-field weed inspections and decision support systems.Advances in Animal Biosciences , Volume 8 , Special Issue 2: Papers presented at the 11th European Conference on Precision Agriculture (ECPA 2017), John

McIntyre Centre, Edinburgh, UK, July 16–20 2017 , July 2017, pp. 860 – 864.
DOI: https://doi.org/10.1017/S2040470017001054

Somerville GJ, Jorgensen RN, Bojer OM, Rydahl P, Dyrmann M, Andersen P, Jensen NP, Green G (2019). Marrying futuristic weed mapping with current herbicide sprayer capacities. Wageningen Academic Publishers, 2017/7/8, Precision agriculture '19, 277-290

Teimouri N, Dyrmann M, Rydahl P, Mathiassen SK, Somerville GJ, Jorgensen RN (2018). Weed growth stage estimator using deep convolutional neural networks. Multidisciplinary Digital Publishing Institute, Sensors, vol. 18, p. 1580.