

Report on the outcomes of a Virtual Mobility

Action number: CA21134

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Title: Digital Technologies for the Transition towards Zero-Pesticide Crop Protection: A Focus on Weed Management

1. Introduction

Modern plant protection is in need of a fundamental change in approach. Intensive crop production systems continue to rely heavily on the use of chemical pesticides, including herbicides, while at the same time there are growing demands to reduce their impact on the environment, biodiversity and human health. COST action CA21134 T0P-AGRI-Network starts from the assumption that gradually increasing the efficiency of existing protection is not enough to reach the ambitious goal of pesticide-free agriculture. The MoU of action emphasizes the need to move from curative to preventive protection based on agroecological principles and for a deep redesign of production systems. It is particularly significant that the MoU states that by increasing efficiency, including precision agriculture and improved decision-making systems, certain reductions in pesticide use can be achieved, but that a significantly greater reduction or complete abandonment of pesticides requires systemic change.

Digital technologies (DTs) can play a key role in crop production systems transition. Their importance is not only in the more precise execution of existing operations, but in the ability to turn a large amount of information about the crop, weeds, soil, weather conditions and plot history into timely and spatially accurate decisions. In this sense, digitization enables the transition from a uniform approach to the whole plot to one in which needs are assessed at the level of a part of the plot, a weed population or even an individual plant.

Weed management is a particularly good example of potential use of digital tools in plant protection. Weed populations are spatially and temporally extremely heterogeneous, their harmfulness depends on the species, density, emergence time and competitive relationship with the crop, and long-term reliance on herbicides has led to the spread of resistant populations. At the same time, a large number of non-chemical measures (crop rotation, cover crops, mechanical, electrical, thermal or laser suppression, etc) require precise knowledge of the place, time and intensity of the appearance of weeds.

Digital approach to weed management should be considered as a continuous process: detection → identification → mapping → risk assessment → decision-making → targeted intervention → evaluation of results → preventive planning for the following seasons. Such an approach goes beyond the concept of "recognize weeds and treat them" and positions DTs as an infrastructure for preventive and integrated weed management.

The aim of this VMG is preparation a synthetic report about the role of DTs in the transition from conventional to plant protection systems with reduced or completely eliminated pesticide application, using weed management as a model for analyzing opportunities, limitations and future development directions.

2. Description of the work carried out during the VM

In the first phase of VMG, grantee done a targeted analysis (mainly based on relevant scientific papers and relevant project reports) of the latest scientific and technological achievements in the field of digital plant protection, with a special focus on digital detection and mapping of weeds, UAV and remote sensing, artificial intelligence and machine learning, decision support systems (DSS), precise application of herbicides, robotic and other non-

chemical measures, as well as digital tools for monitoring and managing weed resistance to herbicides.

A key part of the activity was a virtual expert meeting with TOP-AGRI action participants the organized by grantee. According to initial working plan twelve experts from several COST countries and different areas of expertise were invited, but only 6 responded to invitation. Than additional 15 experts invite to participate, but no one give positive answer. The final group of experts which participate on online meeting consisted of 5 participants. Their expertise includes digital technologies in agriculture and plant protection, UAV and remote sensing, sensors, precision agriculture, site-specific weed management, herbicide resistance, integrated and agroecological weed management. Before the meeting, based on results of literature review grantee prepared a short set of questions focused on the most important technological achievements, examples of successful practical application, technical and economic barriers to the wider adoption of digital technologies and priority research and innovation needs. These questions delivered to the participants who accepted participation.

The grantee moderated the virtual meeting, systematize the conclusions and integrate the participants' contributions into the final report. Special attention was paid to the transition from an approach based primarily on weed detection and treatment to systems that support decision-making, preventive management and precise non-chemical interventions.

The final phase was the creation of a synthetic report, with an overview of achievements, innovation and practical application of digital technologies, identified limitations and recommendations for future research, in the transition towards plant protection systems with minimal or no pesticide use.

The next experts participated in VMG:

Dimitrios Tsitsigiannis (Greece) – expert in digital plant protection technologies and coordinator of the STELLA project. He will contribute expertise in early detection, digital surveillance, sensors, AI and warning systems.

Lena Ulber (Germany) – expert in site-specific weed management, herbicide resistance and non-chemical control, contributing to the integration of digital technologies into precision and integrated weed management.

Anna-Camilla Moonen (Italy) – expert in agroecology, preventive weed management and diversified cropping systems, contributing to the integration of digital and agroecological approaches.

Agnieszka Synowiec (Poland) – expert in weed biology, agroecological and non-chemical weed management and herbicide resistance.

Dragana Božić (Serbia) – expert in weed management, contributing to the integration of digital tools into integrated weed management.

3. Monitoring, detection and mapping of weeds using digital tools

Reliable information on the presence, type and spatial distribution of weeds is the basis of digitally supported weed management. A traditional field survey provides valuable information, but it is time-consuming, depends on the experience of the observer, and can hardly provide detailed spatial information on large areas. The development of sensors, unmanned aerial vehicles (UAVs), satellite systems and cameras on agricultural machines has significantly expanded monitoring possibilities, with different application possibilities in arable crops and orchards.

UAV and remote sensing. UAVs are particularly suitable for weed monitoring because they combine relatively large surface coverage with high spatial resolution. RGB cameras are the most available solution, while multispectral and hyperspectral sensors allow distinguishing vegetation based on reflectance in parts of the spectrum that are not accessible to the human

eye. Modern weed mapping increasingly integrates imagery from UAVs, ground platforms and satellites with machine and deep learning methods. The special value of these technologies is not only the detection of the presence of weeds, but the formation of spatially distribution maps that can be directly linked to subsequent management operations. The key goal is the production of "operational map" that answers the question of where, when and with what measure to intervene. Newer approaches already connect low-budget UAV imaging with the generation of prescription maps for targeted intervention, which represents a significant step from detection to practical management.

Proximal sensing and sensors on machineries. Sensors mounted on tractors, sprayers and autonomous robots are also important for very precise weed management. Such systems can detect plants in real time just before intervention. The advantage is that it is not necessary to separately record and make a previous map, while the main challenges are the short time available for image processing, the high speed of the machine, variable lighting, overlapping plants and the small size of weeds in the early stages.

The greatest practical value is likely to be achieved by combining different data sources. The UAV can identify problem zones at the plot level, while the camera on the robotic platform can distinguish individual plants in those zones and enable intervention with huge precision.

4. Artificial intelligence and decision support systems

Advances in computer vision, machine learning, and especially deep neural networks have dramatically improved the ability to distinguish between crops and weeds. Modern models can perform classification, object detection and image segmentation, enabling the recognition not only that the weed existence but also its location, the area it occupies and the species (under favorable conditions).

The application of AI in weed management shows that the development in recent years has been strongly directed towards deep-learning methods and their connection with UAVs, IoT devices and field robots. However, high model accuracy achieved in experimental datasets does not guarantee equal reliability in heterogeneous real field conditions. Different crops, phenophases, soils, lighting, climate and weed communities can significantly reduce the transferability of models between regions. Therefore, the next stage of development is more important than just increasing the percentage of classification accuracy. The system must translate the information "weed detected here" in an agronomical relevant decision: "is the intervention necessary, which measure is most suitable, when should it be implemented and what the risk is if the intervention is omitted?" In that process DSS have central role. DSS can integrate weed species and density data with crop phenophase, economic damage threshold, meteorological conditions, plot history, crop rotation, previous herbicide treatments and available non-chemical measures. An example of this concept is the new SWIM system for site-specific weed control in corn, which combines RGB images with an economic intervention threshold and generates prescription maps.

For the future protection of plants, the transformation of the DSS from a system that answers the question "should I spray?" to a system that chooses between a number of options: do not intervene, apply a mechanical measure, adjust the sowing date, use a cover crop, perform a targeted non-chemical intervention or, only when necessary, apply a herbicide is particularly important. Digital DSS can help connection between precision agriculture and agroecology through linking monitoring, risk assessment and alternative measures, but at the same time indicate that their application in complex agroecological systems is still limited.

5. From the precise application of herbicides to precise non-chemical interventions

Precise herbicide application. The most developed practical application of digital weed management is currently "site-specific herbicide application". Instead of uniformly treating the entire plot, the herbicide is applied only in places where weeds are detected or where their density exceeds a defined threshold. Systems can use pre-made prescription maps or real-time detection. Smart spraying systems combine a camera, a computer for image processing, an identification algorithm and individual control of the nozzles. A review of many papers on smart spraying technologies shows the intensive development of machine vision and AI detection, but at the same time it indicates that the number of comprehensive field tests of the application systems themselves is significantly lower than the number of studies dealing with weed recognition algorithms. Precise application can significantly reduce the total amount of herbicide and limit the treatment only on the areas where weeds are present. However, from the point of view of T0P-AGRI objectives, this approach has an inherent limitation: it optimizes pesticide application, but does not necessarily change the dependence of the production system on pesticides.

Robotic and mechanical weed suppression. Autonomous ground robots represent an important direction in the development of non-chemical suppression. The combination of RTK-GPS, machine vision system, AI identification and precise actuators enables inter-row, and more and more, intra-row weed removal. A review of robotic technologies shows that systems are evolving from relatively simple automatic guidance to complex platforms that integrate navigation, sensors, weed identification, and various actuators. The main limitations remain to reliably differentiate crops and weeds in all field conditions, cost, operational speed, scalability and integration with existing machinery.

Laser, electricity and other targeted methods. The digital identification of individual plants has opened up the possibility of developing measures that would be difficult to implement without AI and precise positioning. Laser suppression is a good example. The system must first recognize the weed, then precisely determine the position of the sensitive plant tissue and direct a sufficient amount of energy to the target part of weed plant without damaging the crop. Modern laser systems therefore combine three functional levels: target identification, dynamic positioning and precise destruction. Major challenges include speed of operation, variable platform movement, uneven ground surface, overlapping plants and the need to direct the laser to the most biologically sensitive area of the weed plant. A similar concept applies to electrical, thermal and ultralocal mechanical suppression. In the long term, it is likely that one technology will not dominate, but "multimodal robots" that, depending on the type, size and position of the weeds, will choose the appropriate intervention.

6. Digital technologies as support for preventive weed management

The greatest contribution to T0P-AGRI goals will not be achieved if digitization is limited to more efficient application of existing curative measures. A systematic analysis of digital tools in agroecology showed that most applications of digital tools currently relate to monitoring and increasing the efficiency of input use. Therefore, most of the technologies contribute to the first level of agroecological transition (reduction of inputs) while significantly fewer solutions are directed towards higher levels, which involve replacement of inputs and redesign of agroecosystems. This is probably a central question for future digital plant protection.

The digital system should not only use the weed map to determine where to treat, but use multi-year weed infestation information to plan preventative measures. For example, by combining historical weed maps with data on crop rotation, tillage, sowing dates, cover crops and weather conditions, it is possible to identify zones and periods of increased risk. Based on that, DSS can recommend: changing the crop rotation or introducing crops with a different life cycle; use of cover crops; change of sowing dates; stale or false seedbed approach; adjusting the density and spatial distribution of crops; selection of a more competitive genotype; targeted mechanical intervention; prevention of seed production in local hotspots; a combination of

measures adapted to the specific history of the plot. This concept is particularly important because weeds have long-term dynamics. The result of a decision in one growing season affects the seed bank and the problem in subsequent years. Therefore, future digital systems should optimize not only the immediate yield and cost of the intervention, but also the long-term population reduction of problem species.

7. Digital technologies and management of weed resistance to herbicides

Herbicide resistance is one of the areas where digitization can make contribution to early recognition of potentially resistant populations, as well as georeferenced monitoring of their spread, but the potentially the most important level is the integration of resistance risk into the DSS. Such a system could combine: the history of used herbicides and their mode of action, frequency of application, dominant weed species, previous cases of lower efficiency, the presence of confirmed resistance in the region, rotation of herbicide mode of action, available chemical and non-chemical alternatives. Therefore, DSS recommendation to farmer should include herbicide resistance component. It doesn't mean only more precisely selection of herbicide mode of action, but with "diversification of measures".

8. Limitations and barriers to wider adoption of digital technologies

Despite the rapid technological development, the transition from experimental research to routine practice is still slow.

Technical barriers. Reliability of the system under real conditions is still a key issue. A model trained on one crop, soil type or region may not work equally well in another. Weed size, shade, overlapping plants, damage, heterogeneous vegetation and different sensors can affect the results. In such conditions the reliability of precise species identification is questioned. That is why validation is needed across multiple seasons and agroecological conditions. It is expected that for such activities, robots that move on the surface of the plot will be more reliable than UAVs that record from a certain distance. Also, the sensor, the algorithm, the farm-management system and the machine that executes the intervention often belong to different technological ecosystems. For the farmer, an integrated chain of "data → decision → action" is much more useful than a series of independent applications.

Economic barriers. The high initial costs of robots, sensors and equipment particularly limit adoption on small and medium-sized farms. The economic justification depends on the size of the farm, the intensity of the weed problem, the cost of labor, the value of the crop, the degree of reduction of inputs and the possibility of using the equipment in multiple operations. Conclusion is, economic justification and adoption are still not unambiguously resolved and depend on the technological and production context. Economic profitability motivates farmers to accept any new approaches in production including digital technologies. Possible ways to achieve this are state subsidies to support the integration of digital technologies into practice, as well as the joining of smaller farmers in cooperatives for the common use of these technologies.

Knowledge and digital skills. Analyses of precision agriculture adoption show the importance of education, digital competencies, information availability, farm size and expected profitability. The farmer must understand why a particular recommendation was made and have enough confidence to change practice based on it. Due to that "explainable" DSS and simple user interfaces can be just as important as small improvements in the accuracy of AI models. In order for farmers to accept and successfully apply available digital technologies, the support provided by advisors and companies distributing these technologies is very important.

Regulatory and data aspects. The legislation that regulates UAV flights is very strict and it is necessary to make adjustments that will allow the unhindered use of UAVs (with appropriate licensing) in agricultural production. Also, the spread of autonomous platforms opens up issues of safety, responsibility and regulation of machine operation. At the same time, digital platforms are generating large amounts of data about field plots and production practices, making issues of ownership, access, privacy and data sharing an important factor of trust.

9. Priorities for future research and development

Based on the achievements so far, the following priority directions can be distinguished:

1. Moving from detection to decision-making. Further development of DTs should not be focus only by increasing the accuracy and precision of available technologies (which is main focus in nowadays), but key attention must be pay to their transfer in practically applicable DSS in agricultural production.
2. Closing the complete "data-decision-action-feedback" chain. Monitoring, DSS and mechanization must be connected. The system should register the result of the intervention and use it as new information for future decisions.
3. Connecting digitization with agroecological redesign. Digital tools should support crop rotation, crop diversification, cover crops, preventative measures and long-term seed bank reduction, not just herbicide dose or treated area reduction.
4. Development of precision non-chemical weed management. Special priority should be given to robotic, mechanical, laser, electrical and other targeted methods that allow precision weed control without herbicide application.
5. Validation in real production conditions. A large number of technologies show excellent results in controlled or individual experiments. Multi-year and multi-site validation studies involving different crops, weed communities, climatic conditions and farm structures are needed.
6. Involvement of farmers. Technologies should be developed together with end users (farmers). Simplicity, economic justification, maintenance, speed of operation and compatibility with the existing production system must be an integral part of development of digital technologies.

10. Conclusions

DTs are already significantly changing the possibilities of monitoring and suppressing weeds. UAV, remote sensing, computer vision, AI, DSS, smart sprayers and autonomous robots enable the transition from uniform treatment of plots to spatially precise management based on the real presence and intensity of the problem. The most developed systems today can significantly reduce the treated area and the use of herbicides, while robotic, laser and other non-chemical technologies open the possibility of individual treatment of weed plants. However, "accuracy alone does not equal zero-pesticide transition". This is the key message that emerges from both the goals of TOP-AGRI and contemporary literature. Digital technology that enables more precise application of pesticides represents an important step in reducing inputs, but does not change the basic logic of the system if pesticides remain the central means of protection. This is precisely why the TOP-AGRI MoU emphasizes the need for a fundamental redesign and transition from curative to preventive protection.

The next generation of digital plant protection should enable the transition: from detection → to prediction; from map → to decision; from uniform intervention → to site-specific intervention; from a precise herbicide application → to a precise non-chemical measure; from individual infestation control → to preventive system redesign. Weed management represents a suitable area for the development and demonstration of such a concept due to the spatial heterogeneity of weed populations, the problem of herbicide resistance and the large number of available preventive and non-chemical measures. The true potential of digitization will be realized when the technology is not only used to "more precisely treat weeds that have already appeared", but

to integrate information across multiple seasons and help create a production system in which the need for curative intervention is decreasing.

11. Description of the VM main achievements and planned follow-up activities

The Virtual Mobility activity achieved the main planned goals. The activity resulted in a synthesis of the latest scientific and technological achievements related to the role of digital technologies in the transition to plant protection systems with reduced or completely eliminated pesticide application, with a special focus on weed management.

One of the main achievements was the organization of a virtual expert consultation that brought together researchers from five COST countries and different, mutually complementary areas of expertise, including digital plant protection, sensors and automated monitoring, site-specific weed management, herbicide resistance, integrated weed management, agroecology and non-chemical control methods. Although the initial idea to involve a larger number of experts in this meeting was not realized due to lack of interest or inability of invited experts to participate, the meeting enabled the exchange of knowledge and experiences between different disciplines and countries, as well as the collection of expert opinions on technological achievements, practical applications, current limitations and priorities for future research.

The main result of the VM activity was the preparation of a synthetic report that combines the findings of a targeted literature analysis and the conclusions of an expert consultation. The report emphasized the need to move beyond an approach where digital technologies are used only for weed detection or more precise pesticide application, and to move towards systems that support decision-making, preventive management and the increasing use of precision non-chemical interventions. Special attention is paid to UAV and remote sensing technologies, artificial intelligence and machine learning, sensors, decision support systems, site-specific management, robotic technologies and possibilities of integrating digital tools with agroecological approaches.

The activity directly contributes to the goals of the TOP-AGRI action by strengthening research coordination between participants from different countries and disciplines, as well as by identifying opportunities, barriers and research priorities relevant to the transition to plant protection systems with minimal or no pesticide use. The synthetic report will also contribute to knowledge integration within the COST action.

The cooperation established during the VM activities represents the basis for further exchange of knowledge in the field of digital plant protection and integrated weed management. The possibility of developing future joint research activities and participating in European projects dedicated to digitization, precise weed management and reduction or elimination of pesticide use was considered. It was concluded that future projects should focus on integration existing digital plant protection tools into farm decision-making and crop protection practice.