Precision Weed Management Techniques For Smart Agriculture

Gayatree Mishra[1], Ashok Kumar Mohapatra[2*] and Sweta Rath[1]

[1]*Assistant Professor, Department of Agronomy, Faculty of Agricultural Sciences, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, India*

[2]*Professor, Department of Agronomy, Faculty of Agricultural Sciences, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, India*

**Corresponding author email: ashokmohapatra1957@gmail.com*

Abstract:

The increase in the world's population has created a need to produce more food, generating, consequently, greater pressure on agricultural production. In addition, problems related to climate change, water scarcity or decreasing amounts of arable land have serious implications for farming sustainability. Weeds can affect food production in agricultural systems, decreasing the product quality and productivity due to the competition for natural resources. In this sense, there is a need to carry out an effective and sustainable weed management process, integrating the various control methods (i.e., cultural, mechanical and chemical) in a harmonious way, without harming the entire agrarian ecosystem. Thus, intensive mechanization and herbicide use should be avoided. Herbicide resistance in some weed biotypes is a major concern today and must be tackled. This became real beginning 1957 in U.K., Hawaii, USA and Canada in the case of 2,4-D. With continuous use of same group of herbicides since that time, herbicide resistance has become a significant global problem. In this situation, weed scientists need to look for alternative weed management approaches that enhance agricultural productivity in smart agriculture. On the other hand, the recent development of weed control technologies can promote higher levels of food production, lower the amount of inputs needed and reduce environmental damage, invariably bringing us closer to more sustainable agricultural systems. One such alternative is precision weed management (PWM) which is inclusive of those methods that will ensure greater farm productivity. These include a combination of need-specific, site- specific and cost-effective weed sensing systems (ground-based and aerial-based) in addition to integrated weed management that includes chemical, mechanical, manual and cultural methods. Weed scientists need to look ahead to explore and develop a combination of these methods for the benefit of farming community by reorienting their future research programs in this direction.

Keywords: Integrated weed management, Precision weed management, Sustainability, agricultural production.

1.1 Introduction

Weeds have been present since the beginnings of civilization and are not likely to disappear in the near future. It is well known that weeds pose a recurrent and ubiquitous threat to agricultural productivity (Buhler *et al*., 2000). Weeds constitute a major constraint to global agricultural productivity. The world population has rapidly exceeded seven billion and is expected to reach nine billion by 2050 (Young, 2014). Current crop production levels are not adequate to feed the growing population, and meeting this anticipated demand could be a huge challenge for humanity. Climate change, the scarcity of arable land and water resources and the threat from diseases, pests and weeds are additional issues that make the pressure on agricultural systems greater than ever before, with implications, in the short and long term, for sustainability, for the planet and for the quality of life of living beings. Weeds have been a persistent problem in agriculture since its beginning. Weeds hinder the growth of crops by competing with the plants for water, nutrients and sunlight, which results in large losses in crop production. Most weeds are either controlled mechanically through specific cultivation practices or with the application of herbicides. However, intensive mechanization increases soil erosion, leading to a loss of fertility. The use of herbicides contaminates the soil, water, food and air, causing diseases in humans and animals (Ribas, 2009), creating the phenomena of herbicide resistance and unbalancing ecosystems. From this perspective, biodiversity plays a preponderant role in the provision of ecosystem services in agricultural systems.

Agrobiodiversity can have a direct effect on services when increased crop diversity increases food resources, or when cover crop diversity increases plant biomass, improving water quality and lowering runoff. However, agrobiodiversity and services, such as pollination, improved soil structures and natural pest control, are increasingly threatened by the massive elimination of weeds and wild plants, as well as due to species toxification by agrochemical inputs (Anonymous, 2017). Weeds perform a range of ecosystem functions in terms of soil quality and biodiversity support, which can help to sustain agroecosystem productivity in the long term (MacLaren *et al.,* 2020). Thus, as sustainable agriculture has the capacity to save natural resources for the future and develop farms with less cost, a transition to sustainable weed control is necessary for a variety of environmental, social and economic reasons (Monterio and Santosh, 2022). During the last few years, agriculture is undergoing a fourth revolution (Farming 4.0) by integrating Information and Communications Technologies (ICT) in traditional farming practices (Sundmaeker *et al*., 2020). In smart farming, a wide range of agricultural parameters can be monitored to improve crop yields, to reduce costs and optimize process inputs, such as environmental conditions, growth status, soil status, irrigation water, pest and fertilizers, weed management, and greenhouse production environment. Smart farming is a green technology approach, since it reduces the ecological footprint of traditional farming (Nukala *et al*., 2016).

Sustainable weed management comprises a suite of weed management options, including integrated weed management (IWM), which is based on the employment of a multiplicity of weed control strategies. IWM aims to optimize crop production and increase grower profit through the concerted use of preventive strategies, scientific knowledge, management skills, monitoring procedures and the efficient use of control practices (Hartzler and Buhler, 2007). The current weed control practices lack the precision needed to control weeds effectively and safely without harmful side effects. Farmers in many regions rank weed control as their major production cost. In conventional systems, herbicide resistance, and off-target movement of applied herbicides, have left many growers with few alternatives. Even if they are adopted, biotech crops pose a serious concern about their biosafety in the long run. Biosafety issues have become a crucial limitation to their further development (Rao, 2018).

In this context, a wide and rapidly expanding range of new technologies have been developed and implemented in agricultural practices, which also play a key role in progress towards economically and environmentally sustainable weed management. Precision weed management leads to a reduction of inputs without decreasing weed control effectiveness. Studies and experiments have shown significant potential savings and technical progress in sensing, weeding and spraying technologies. Some of these technologies have been commercially exploited (Christensen *et al*., 2009).

1.2 Drawbacks of Conventional and Non-Conventional Method of Weed Control

Apart from the advantages of using herbicides for weed control, there are also disadvantages, mainly due to limitations of the conventional spraying technologies. Continuous use of the same group of herbicides over a period of time on the same piece of land leads to ecological imbalance in terms of weed shift, herbicide resistance in weeds and environmental pollution (Gnanavel, 2015). Indeed, the overuse of herbicides with the same mode of action may lead to the development of herbicide-resistant weed populations. As a result, agricultural landscapes now tend to be dominated by a few weed species that are difficult to control and that provide a poor resource for farmland biodiversity (Rueda-Ayala *et al*., 2020). For example, cutleaf evening primrose (*Oenothera laciniata*) has become resistant to glyphosate and paraquat (Sims *et al*., 2018). Weed resistance to herbicides has led to the development of crops resistant to previously non- selective herbicides. Around 190 M ha land around the world have been under biotech transgenic crops in 2019 (ISAAA, 2019). Around 80% of this area was under herbicide-resistant ones, either alone or stacked with insect resistance. Herbicide-resistant (HR) biotech crops have made a positive contribution to global crop production and the economies of farmers (Beckie *et al*., 2019), while they certainly raised concerns about biosafety to consumers.

Herbicides can also have negative side effects, such as surface and ground water contamination, as well as leaving herbicide residues in the food chain (Lancaster, 2021). In addition, chemical herbicides can substantially decrease the soil microbial communities and earthworm populations, and the persistent effects of weed suppression can lead to the reduction of nutrient availability and soil biodiversity (Mia *et al*., 2020).

In the same way, the excessive use of tillage results in substantial harmful effects on the soil quality parameters, including biological diversity, soil structure and water storage capacity. Tillage reduces the supply of carbon and nitrogen nutrients to microorganisms. Soil erosion and soil degradation, inherent in tillage-based systems, increase the environmental pollution from agricultural chemical inputs, such as fertilizers and pesticides, compromising the sustainability of crop production and ecosystem services, as well as threatening global food security in the long run. Moreover, the operation may face limitations owing to adverse weather conditions. There are also potential problems associated with minimum tillage or non-tillage. The bulk density and compaction of the topsoil increases, and the phytosanitary situation worsens with a higher spread of fungal diseases and the weed infestation of crops (Peera *et a*l., 2020). Furthermore, farmers using reduced tillage may choose to rely increasingly on herbicides and pesticides to deal with these threats and, as a result, the phytotoxicity of the soil increases (Monterio and Santosh, 2022).

Ground cover methods, flaming or livestock grazing for weed control also have a few limitations. For example, mulching is cost intensive on a large scale, can promote changes in the soil due to the continuous use of the same mulching material and some of the organic mulches have allelopathic effects on crops (Peera *et al*., 2020). In addition, many types of organic mulching, such as grass and straw, contain seeds which could allow weeds to grow and acidify the soil. Cover crops incur expenses for novel equipment, more complicated management practices and time spent seeding and eliminating cover crops instead of managing cash crops. Living mulches can reduce main crop growth and yield due to competition for water and nutrients, increase pest populations and the risk of diseases. Moreover, living mulches can also promote allelopathy (Dabney *et al*., 2001). Soil solarization induces high temperatures that can be lethal to bacteria and fungi. In some species, if the lethal temperature is not reached, dormancy can be broken, allowing an emergence of a new flush of weed seedlings. This can occur along the topsoil layer (Sims *et al*., 2018). Solarization tends to result in a flush of nutrients which should be managed by immediately establishing the crop after plastic removal to prevent nutrient loss. In a flaming strategy, fuel and water consumption can be high, and the flame has restrictions for use during the summer from a fire prevention standpoint. However, smaller, more portable units are now available and provide another tool for the spot control of escape weeds or around sheds and other pieces of infrastructure (Pannacci *et al*., 2017). Finally, weed control via livestock grazing can cause damage to the soil structure and non-target species, lead to the spread of weed seeds in feces or on wool, hair or hooves, or even cause the loss of animal condition or liveweight (Popay and field, 1996).

Some of the limitations described above can be mitigated or even eliminated when technology associated with precision weed management is integrated. The use of the internet, the various types of sensors, artificial intelligence or machine learning can provide potential improvements to IWM. It may be said that we are entering a new era of agriculture, Agriculture 4.0, where precision is the rule (Santos and Kienzle, 2020).

1.3 Advanced Techniques for Weed Management

Managing weeds has always been placed at the centre of agricultural activity by farmers since ancient times. The control of weeds is a big challenge in agriculture and in many cases a complex, controversial and also expensive problem to solve. In fact, weed management accounts for nearly one third of the total cost of the production of field crops (Gnanavel, 2015). This agronomic practice goes beyond the control of existing weed problems and places greater emphasis on preventing weed reproduction, reducing weed emergence after crop planting and minimizing weed competition with the crop (Monterio and Santosh, 2022).

Currently, weed management in agricultural systems branches out into two distinct directions corresponding to different approaches. On the one hand is the widespread use of synthetic herbicides, while on the other, weed control is widely based on mechanical, cultural and physical methods (Scavo and Mauromicale, 2020). Mechanical methods are generally inefficient, while herbicides have a negative impact on the ecosystem. In this regard, mechanical and chemical weed control has disadvantages that will probably impede their effectiveness for future weed management. Thus, weed management requires an integrated approach that minimizes the drawbacks of mechanical and chemical weed control (Sims *et al*., 2018). Indeed, there is a great need for a new weed management paradigm in modern agriculture that is based on ecological principles and non-conventional weed management approaches. Sustainable weed control for the crop can significantly influence the operation of machinery, the reduction of pest habitats (e.g., for voles) and make contributions to satisfactory economic benefits through the quality of harvested products, as required by the market (Hammermeister, 2016).

IWM plays a key role in the weed management of the advanced cropping systems of developed countries, especially in the European Union, while it is still poorly adopted in developing countries. A combined use of different weed control methods (agronomic, physical, mechanical and chemical) within a system, rather than relying on a single method, is required in IWM.

This strategy is important for reducing the selection pressure for the development of resistance to any single method of weed control (Chauhan, 2020). Furthermore, the use of non-chemical weed tactics in minor crops is important due to the scarce availability of chemical compounds. Unlike traditional processes, IWM integrates many agroecological practices, such as the role of conservation tillage and crop rotation on weed seed bank dynamics, the ability to predict the critical period of weed interference and its competition with crops, and the specific critical levels of crop or weed interaction (Sims *et al*., 2018).

Besides, current weed control practices lack the precision needed to control weeds effectively and safely without harmful side effects. Farmers in many regions rank weed control as their number one production cost. In conventional systems, herbicide resistance, and off-target movement of applied herbicides, have left many growers with few alternatives. Success of ground-based and aerial-based remote sensing systems depends on the size of farm holdings and costs. This technology is more apt for larger land holdings. Therefore, despite good promise, precision weed management (PWM) is unlikely to be a commercial success in India in near future. Over 85% of farm holdings in India are less than 2 ha. This is likely to go up to 91% by 2030. However, small holdings account for only 45% of the land under cultivation.

Over-reliance on any one method of weed management can overtime reduce its efficacy against weeds. Just as using the same herbicide continuously can lead to resistance as mentioned earlier. Therefore, the need-specific integrated weed management (IWM) is a better option. IWM is based on diversification. IWM requires tactics beyond herbicides. These include pre-planting, post-planting and post-harvest management measures. Two factors to be considered when developing IWM plan include: a) target weed species and b) time, resources and capabilities required to implement it.

In a broader context of IWM, emerging technologies have the potential to change the current approach to weed control and help significantly reduce environmental impacts, such as herbicide resistance or drift and the high cost of inputs and labour, without decreasing weed control efficacy. Several methods are being developed to observe and detect weeds so that control measures can be applied wherever and whenever they are needed. This paradigm shift is based on an interdisciplinary work to harness powerful technology tools and use them to control weeds (Young, 2014). From this perspective, we will present in the next section the Precision weed management contributions to weed control, which could be considered to be an important upgrade in IWM (Monterio and Santosh, 2022).

1.4 Precision Weed Management

Generally, weed management inputs are applied uniformly to the whole field, like most other crop, soil, and pest management practices. However, the occurrence and intensity of weeds are not uniform across the field. They are more often patchy (aggregated or clumped) and uneven due to several agro-ecological factors. Therefore, uniform herbicide application across a field, where target weeds are not uniformly distributed, can waste resources. This may lead to adverse economic, environmental and social concerns about herbicide use. Gerhards *et al*., (2002) achieved herbicide savings of 60% and 92% for dicot and monocot weeds, respectively, in spring barley cultivation, and 11% and 81% for the same weed groups in maize. Normally, the need for herbicide application ranges between 7% and 64% of the total area, suggesting the saving of herbicide used. The spatial heterogeneity of weeds and possibility of reduction in herbicide quantity used has inspired several weed scientists to research on to better weed management practices. One such practice is precision weed management (Rao, 2021).

Precision weed management (PWM) offers a set of powerful tools to increase the efficiency of weed management by offering the following benefits:

1. Lowers herbicide costs and environmental problems, with greater weed control efficiency and leading to greater acceptance of herbicide usage.

2. Helps use of optimal quantity of management inputs on the target weeds at the right time.

3. Reduces wasteful application of inputs for better environment.

4. Delays, and even possibly eliminates, evolution of herbicide-resistant weed species.

5. Reduces accumulation of herbicide residues in soil, water and environment.

6. May possibly reduce or avoid herbicide toxicity on crops.

Several PWM methods are being developed to scout and detect weeds so that control measures can be applied where and when they are needed. Two such measures include (1) site-specific weed management and (2) robotic technology. These include various other alternative methods in addition to chemical method.

1.4.1 Site-specific weed management

Site-specific weed management (SSWM) technique includes utilization of machinery or equipment embedded with technologies that detect weeds growing in association with crops to maximize their successful control (Brown and Noble, 2005; Christensen *et al*., 2009). It is based on the concept of adjusting the intensity of management practices to the actual degree of weed infestation, with only those areas having a weed density at a threshold level that requires treatment (Hamouz *et al*., 2013). If applied at the required quantity of herbicides at threshold weed density level at which crop growth will likely suffer due to weed competition the use may be reduced considerably by 40–60%. Different selective herbicides are applied, alone or in a tank-mix, on weed-infested areas to control broad-leaf and grass weeds differently. For this to be effective, SSWM requires the precise setting of threshold levels for effectiveness and reliability.

Success of SSWM technologies depends on three key elements (Christensen *et al*., 2009):

1. A weed sensing system which identifies, localizes and measures crop and weed parameters.

2. A weed management model that helps applying knowledge and information about crop-weed competition, population dynamics, biological efficacies of control methods and decision-making algorithms, and optimize treatments according to the density and composition of weed species.

3. A precision weed control implement which includes a sprayer with individual controllable boom sections or a series of nozzles that enable spatially variable applications of herbicides.

Another essential part of SSWM technology is the heterogeneous agro-ecosystem encompassing individual crop and weed plants. These could be small units of individual plants, clusters or patches of plants within a field, or even a whole field. In terms of weed management, the hierarchy reflected in the spatial resolution within a farm may follow four levels (Christensen *et al*., 2009):

1. Treat individual plants using highly accurate spraying nozzles, controllable mechanical implements or laser beams.

2. Treatment of a grid adapted to the resolution e.g. adjust the spray with a nozzle or a hoe unit.

3. Treat weed patches or subfields with clusters of weed plants.

4. Treat the whole field uniformly.

1.4.1.1 Weed sensing systems

There are two categories of weed-sensing systems: ground-based and aerial-based, (Wang *et al*,. 2019) using digital cameras or non-imaging sensors. In large areas, the most cost-effective approach would be remote sensing, using aircraft or satellites to provide a farm with maps of weed occurrence (David and Brown 2001; Fernández-Quintanilla *et al*., 2018).

1.4.1.1.1 Ground-based sensing system- In this, multi- spectral imaging sensors such as colour digital optical cameras are used in a mobile platform that has a sprayer. It works better in the case of spatial treatments at field resolution levels 1, 2 and 3 (Christensen *et al*., 2009). Greater proximity reduces the pixel sizes to millimeters or smaller. This helps in analyzing images of species-specific features, such as shape, texture and plant organization. With spatial resolution lower than 1 mm, images collected from ground-based camera systems and subsequent image processing routines will help delineating individual weed plants from the crop plants (Thorp and Tian, 2004). As much greater computational load is on the sprayer control system, it detects and identifies weeds and then determines and administers the appropriate action in real time (Brown and Noble, 2005). Data must therefore be processed at a very high rate for the sprayer to progress at a reasonable speed. Unlike the aerial mapping approach, there are no additional tasks and infrastructure required.

1.4.1.1.2 Aerial-based remote sensing (ARS) system- This airborne remote sensing, done from either an aircraft or a satellite platform, requires two things. First: suitable differences in spectral reflectance or texture must exist between weeds and their background soil and plant canopy. The second requirement is remote sensing instrument must have sufficient spatial and spectral resolution to detect weed plants. ARS methods can be successfully applied to detect distinct weed patches which are dense and uniform, and have unique spectral characteristics (i.e. weed patches larger than 1×1 m). Therefore, this method is only applicable for whole-field treatments or to treat weed patches or sub-fields with clusters of weed plants. A major disadvantage of ARS is that it can be difficult to acquire the data when needed, particularly if weather conditions are not ideal when the satellite or the aircraft passes over. In this situation, data acquisition can be delayed for days or weeks (Christensen *et al*., 2009).

The current knowledge on the utility of Unmanned Aircraft Systems (UAS) platforms and remote sensing tools for weed monitoring and precision weed management were reviewed recently (Singh *et al*., 2020). Despite studying a wide range of weed sensing techniques and modest advancement in weed mapping and control software available for precision agricultural practices over the past few years, few farmers have so far adopted site-specific management of weeds. No technique has been developed into a commercial product till now. The economic and technological limitations for SSWM may preclude its widespread adoption. However, as research is developed and technology refined, costs lowered, the opportunities for site-specific management of weeds at the farm level will greatly increase.

1.4.2 Robotic technology

In the recent past, the dawn of robotic technology has become an alternative option to site-specific weed management. This evolutionary step in precision agriculture including weed management is very much like hand hoeing or knap-sack spot spraying but without the need for a human presence (Osten and Crook, 2016). An agricultural weeding robot consists of hardware and software and it has an unmanned, self-steered platform that hosts an array of weed detection units. These, in turn, activate an array of weeding tools whether it is spray nozzle, microwave unit or tillage tool (Osten and Crook, 2016). Agricultural robotic systems will be multi- purpose (sowing, fertilizing, spraying, scouting, counting, sensing, etc.), multi-model (chemical, mechanical, electrical, thermal weed control) and long-enduring to reduce the need for tractor work (Perez and Gonzalez, 2014). They will reduce both soil compaction and labour requirement. Currently, a wide array of robotic machines and systems has been developed across the world. These include Hortibot, Robocrop, IC-Cultivator, Robovator Hoeing Robot, Thermal Hoeing Robot, EcoRobot, Ladybird, Bonirob, AgBot, Swarmbots, RIPPA, etc. (Rao, 2018).

1.4.2.1 Hortibot: It is a semi-autonomous robot with a navigational platform fitted with different weed management tools to either mechanically remove weeds or precision-spray them. It uses a vision-based system of downward-focussed cameras to navigate around the crop. It is equipped with a computer and GPS to find the exact location of weeds and plants. It can manually pick weeds, spray or remove them by using flames or a laser. It will spray herbicides exactly above the weeds. This eco-friendly robot, weighing 200–300 kg, can identify around 25 different kinds of weeds (https://www.zdnet.com/article/hortibot-a- weed-removing-robot/). Further improvements can allow it to more number of weeds.

1.4.2.2 Robocrop: It is the first commercially available robotic weeding machine. It was developed by Tillet and Hague Technology Ltd, in U.K. It utilizes a forward-looking camera that detects crop plants and a set of rotating disc blades mounted on an off-centre shaft that cultivate around the crop plants within the row. Its inter-row precision guidance system uses a digital video camera to capture images of the crop within the row. These images are analyzed to find the position of the individual plants. This information is then utilized for lateral steering of the hoe and individual synchronization of the In-Row Weeder disc, which is controlled via the parallel linkage wheel unit. Rotation of the disc is synchronized with forward movement and the plant positional information from the imaging camera. Robocrop programs the computer to constantly adjust the rotational speed of disc to suit the variability of plant spacing. It removes up to 3 plants per second per row. A 6 m wide system with a plant-spacing of 50 cm travelling at 5.4 km/h may cover 3.2 ha/h. This robot machine can cultivate over 98% of the area. It, however, does not operate effectively in rows with densely and or irregularly spaced crop plants, and where weeds and crop plants are similar in size.

1.4.2.3 IC cultivator: Developed in the Netherlands in 2012 and released in Europe in 2013, IC cultivator uses hooded cameras with artificial LED (light- emitting diode) lighting on each planted row to identify crop plants. As the machine moves forward, a pneumatic cylinder opens and closes a set of cultivator knives into the seed line around the crop plants to uproot weeds. A camera detects the plant and sees the row pattern. The width of this hydraulically-operated modular how blade ranges from 1.5 to 6.0 m, with a hoeing capacity of 3–4 plants/sec at an operating speed of 3- 4 km/h.

1.4.2.4 Robovator hoeing robot: Developed in Denmark, Robovator Hoeing Robot is similar in concept and operation to the IC-Cultivator but it is non-hooded with artificial lighting for consistent image quality. In this, the robot is equipped with a special plant detection camera above each row. It has a mechanical tool which is operated by hydraulic power. The "intelligent" weeding tools normally stay in the row, but they move out of the row when a crop plant is passing. The specially designed plant detection cameras fitted on each parallelogram continuously monitor the passing plants. If a crop plant passes, the computer will send a signal to the hydraulic controlled tool which at the specified time will be moved out of the row. When the crop plant has passed, the tool will be moved into the row again. If there is a gap in the row, and one or more plants are missing, the tool will just stay in the row. The automatic lateral control will make sure that the machine stays in the exact position even if the tractor goes off track.

1.4.2.5 Thermal Hoeing Robot: Thermal hoeing robot, also developed in Denmark, utilises the Robovator vision system to identify crop plants. A series of plasma jets are oriented towards the crop row that deliver flame to kill weeds. Multiple jets are used to deliver a sufficient quantity of heat to kill them. It operates at 1–6 km/h.

1.4.2.6 EcoRobot: Developed in Switzerland by Ecorobotix, EcoRobot is a small revolutionary robot for ecological and economical weeding of row crops. The robot performs weeding by combining an advanced vision system that recognizes weeds and a faster robotic arm to remove them either by spot spray or spinning disk. It is light-weight and easy to transport. It is solar-powered and can run for several days performing weed control with 95% efficacy.

1.4.2.7 Ladybird: Named after its resemblance to the beetle (Blucher, 2014), Ladybird was developed at the University of Sydney's Australian Centre for Field Robotics (ACFR) for use on commercial vegetable farms to undertake autonomous tasks such as mapping, surveillance, classification and detection of a variety of vegetables and weed control. This omni- directional solar-electric powered ground vehicle is fitted with sensors (lasers, stereo and hyper-spectral cameras) to detect vegetable growth, weeds and animal pests. A robotic arm for removing weeds but with autonomous harvesting potential is also fitted to Ladybird (Hollick, 2014).

1.4.2.8 Bonirob: Bonirob was developed by Deepfield Robotics of Bosch, Germany. It is the size of a small compact car. It moves around the field using video and LIDAR (Light Detection and Range)-based positioning as well as satellite navigation, and it knows its location to the nearest centimetre. LIDAR is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. Bonrob is capable of distinguishing between weeds and crops by comparing them to images using machine learning. These include several factors for the analysis, such as leaf colour, shape and size. Fitted with a rod, weeds are mechanically controlled by a simple but swift ramming into the ground (Anonymous, 2015) like a punch, rather than with herbicides. Bonirob punch is considered a better solution since it involves only one action compared to pulling out a weed which requires grasping and then doing something with it. The punch or ramming is fast (0.01 sec) and easy making it a task well-suited to a robot. The onboard generator allows it to operate for 24 h without needing to refuel.

1.4.2.9 AgriBot: Agribot is a light-weight, golf-buggy sized robot designed as an autonomous vehicle by Queensland University of Technology, Australia. The newer prototype AgriBot II helps farmers with seeding, fertilizer application and weed control (Bryant, 2014). It uses myriad sensors, software and other electronics to make its way through a field while detecting, accurately classifying and destroying weeds. Weed destruction is carried out by herbicides applied with pinpoint accuracy, reducing waste or through a mechanical hoe. Mechanical removal is used on weed species that have become herbicide resistant. This solar-powered Weed Terminator, Agribot II which can reduce the costs of weeding crops by around 90%.

1.4.2.10 RIPPA: RIPPA (Robot for Intelligent Perception and Precision Application) is being developed by the Australian Center for Field Robotics at Sydney University. This autonomous solar-powered and battery-operated ground vehicle has an ability to collect data using sensors that also map the crop area and detect weeds. It is fitted with a smart applicator to apply the herbicide at correct dose at a high speed. Currently, this machine can estimate crop yield, spray weeds and fertilizer, and can operate up to 21 hr in one trip.

1.5 Future Line of Research for Adoption of Precision Weed Management Techniques

Weed scientists of next generation will face challenging issues in developing and implementing best weed management practices. Herbicides will continue to be used, though perhaps in a more limited fashion. Therefore, intensive training in herbicide chemistry, physiology and technology must continue. Weed biology will continue to grow in importance because of growing weed resistance to herbicides. Development of herbicide resistant biotech crops will continue, despite problems in their adoption over long time. Precision weed management, now in initial stages of development, will grow. All of these require weed scientists develop skills in the following:

1. Fundamental mechanisms underlying plant-plant interactions.

2. Plant population modelling.

3. Weed genomics (genome sequencing), metabolomics (metabolome analysis) [Rao 2018] and methods of high-throughput screening of herbicides.

4. Evolution of resistance of weeds to herbicides, particularly non-target resistance; their infestation and spread.

5. Approaches to improve crop competition with weeds. These include altered crop growth response, allelopathy, etc.

6. Precision weed management and robotics technologies automated recognition of weeds and invasive plants (machine vision, geographic information systems and remote sensing, etc.).

7. Precision weed management technologies in regard to chemical and physical, novel methods.

8. Collaboration with software specialists and engineers to develop new and improved ground- based and aerial-based remote sensing systems.

Training and involvement of weed scientists in these technologies are required to have a paradigm shift in weed management (Rao, 2021).

1.6 Economic Aspects, Commercial Adaptation and Ecological Benefits

Acceptance of chemical crop protection is decreasing in the society. Pesticides are often considered as contaminants, which may affect food safety and hurt the ecosystems. This concern is reflected in political steps and legislative regulations. The use of herbicides was been restricted and probably will be more restricted due to their unfavourable ecotoxicological profiles or other environmental concerns (European Commission, 2019). The Commission targets set by the Green Deal and Farm to Fork strategies are to reduce the overall use and risk of chemical pesticides by 50% until 2030, promoting greater use of safe alternative ways of pest management (European Commission, 2020). To comply with these targets and to keep up with future environmental policy measures, farmers will be forced to adopt new technologies including SSWM.

Another factor, which is likely to increase the demand for environmental-friendly weed management methods, is the growing area of organically produced foods. The total organic area in the EU-27 was nearly 14 million hectares in 2019, which corresponds to 8.5% of the total utilised agricultural area of those countries. The increase in organic area between 2012 and 2019 was 46% (Eurostat, 2021). The new Action Plan for the development of organic production in the EU sets a target of 25% area of organic farming until 2030 (European Commission, 2020).

Although the precision agriculture technologies (including robotics) are generally considered to have a potential for improving farm productivity and profits (Bongiovanni and Lowenberg-DeBoer, 2004), adoption of SSWM is more complex. Application of SSWM technologies may be diverse and may be realised under various environmental and economic conditions. A key question is what operations have to be substituted by the new technologies. Replacing manual weeding by robotic weeding platforms will certainly increase productivity (Perez-Ruiz *et al*., 2014; Sorensen *et al*., 2005). Although these manual operations are so far rather infrequent in developed countries, the increase in organic farming creates a significant potential for this technology. The farmers, however, still hesitate to invest in precision weed control technologies as the calculation of the profitability is not straightforward. By implementing robotics, many factors such as the purchase price, annual utilisation, area capacity and weeding efficiency have to be considered. Some parameters such as overall life-time and maintenance costs of SSWM have to be first proven by their long-term operation. The barriers for adoption of SSWM technologies may not be just economic. The farmers are justifiably concerned about additional works, which will place more demands on their technical and IT literacy (Balafoutis *et al*., 2020).

For site-specific herbicide application, Gerhards and Oebel, (2006) reported a 50% decrease in herbicide costs. However, this figure will depend on the actual density and aggregation of weed populations. Nevertheless, this technology may only be profitable if weed infestation is low and if the equipment and time needed for weed detection and variable herbicide application will not introduce a substantial increase in treatment costs (Swinton, 2005). Andujar *et al*.,

(2013) simulated control strategies for *S. halepense* in maize crops. Site-specific weed management was the most profitable strategy when <19% of the field was infested. Robotic weeding in organic farming can reduce labour costs and allow farmers to extend the production of labour-intensive crops or even practice more profitable crop rotations. Conventional farms using SSWM might realise higher selling prices for their agricultural products (Lowenberg-DeBoer *et al*., 2020).

The integration of SSWM technologies in conventional farms will probably be driven by their environmental benefits, mainly the significant reduction in herbicide use. Economic aspects, such as reducing yield losses by herbicide-resistant weed populations and reducing herbicide costs, will also favour this technology. However, high efficiency and relatively low costs let farmers often decide for chemical weed control (Swinton, 2005). To make SSWM technologies more attractive for farmers, they have to provide more significant competitive advantages, such as higher selling prices for low-residue production or direct and indirect subsidies for the purchase and operation of precision farming technologies. Agro-environmental policies can be applied to push the farmers towards the adoption of more environmentally friendly weed management methods. Currently, however, there are no direct regulatory measures to adopt precision agriculture technologies in the EU (Barnes *et al*., 2019).

A second benefit may be the enhancement of weed biodiversity through a more selective weed control, focussing only on undesirable weed species. Rare, beneficial or endangered species can be identified, located and excluded from treatments. On the contrary, newly introduced invasive species can be eliminated before they create a persistent seedbank. The use of SSWM can promote more diverse crop rotations. Various crops that are currently discarded by growers because of the limited options available for weed control can gain in attractiveness for growers. An additional environmental benefit of robotic weeding machines is the reduction in fuel and carbon consumption and less soil compaction associated with the use of small robotic weeding units.

Conclusions

With the growth of the world population and the consequent need to ensure the supply of food by increasing agricultural production, there is a need for improved management of the world's agricultural resources while minimizing the negative impact on the environment. From an agronomic point of view, weeds are considered to be a threat with serious implications for agricultural efficiency, causing yield losses. However, from an ecological perspective, they can also be considered to be valuable indicators of biodiversity in the agrarian ecosystem, as well as providers of ecological services as a component of the agroecosystem. Weed management involves several methods. Nevertheless, a single method of control will not provide adequate long-term weed management, and instead often results in increasing resistance. Therefore, the need to integrate different weed control methods under a holistic approach is critical.

The use of herbicides creates imbalances in the ecosystem, even causing the resistance of some species to the continued use of these chemical agents. In addition, no less serious are the environmental problems they cause and their consequent threat to the well-being and health of animals and humans.

Thus, the sustainable management of the agricultural system, namely of weeds, is an important issue for the present and future of humanity. In addition to integrated management, the development of precision technologies inherent to weed control can be a valuable contribution to improved sustainability and agricultural yield in smart agriculture. In this sense, suggestion would be more effective involvement of researchers and farmers with the integration of ecological and technological principles into weed management decision making.

References

Andujar, D., Ribeiro, A., Fernández-Quintanilla, C. & Dorado, J. 2013. Herbicide savings and economic benefits of several strategies to control *Sorghum halepense* in maize crops. *Crop Protection*. **50**:17–23.

Anonymous. 2015. Intelligence for the fields: Bosch robot gets rid of weeds automatically and without herbicides. Bosch Deepfield Robotics I News I October 8, 2015 [*URLhttp:// www. deepfieldrobotics.com/en/News-Detail_ 151008. html*].

Anonymous. 2017. PAN—Pesticide Action Network Europe. Alternative Methods in Weed Managment to Glyphosate; Intergrated Weed Management. Pesticide Action Network Europe: Brussels, Belgium, 2017. Available online*:* *https://www.pan-europe.info/sites/pan-europe. info/files/Report_Alternatives%20to%20Glyphosate_July_2018.*

Balafoutis, A.T., Van Evert, F.K. and Fountas, S. 2020. Smart farming technology trends: economic and environmental effects, labour impact, and adoption readiness. *Agronomy*. **10**: 743.

Barnes, A.P., Soto, I., Eory, V., Beck, B., Balafoutis, A.T., Sanchez, B. *et al*. 2019. Influencing factors and incentives on the intention to adopt precision agricultural technologies within arable farming systems. *Environmental Science and Policy*. **93**: 66–74.

Beckie, H.J., Ashworth, M.B. and Flower, K.C. 2019. Herbicide resistance management: Recent developments and trends. *Plants*. **8**: 161; *doi:10.3390/plants8060161*.

Blucher, A. 2014. World first farm robot set to revolutionise vegetable farming. ABC Rural News webpage. [*URL http://www.abc.net. au/news/2014-06-25/farm-robotics- university-of-sydneyvegetable-farming/5550076*].

Bongiovanni, R. and Lowenberg-DeBoer, J. 2004. Precision agriculture and sustainability. *Precision Agriculture*. **5**: 359–387.

Brown, R. and Noble, S. 2005. Site-specific weed management: Sensing requirements-what do we need to see. *Weed Science*. **53**(2): 252–258.

Bryant, S. 2014. Could weed-zapping Daleks be the new farmer's friend, with robots roaming crops? ABC Rural News webpage. [*URL http://www.abc.net.au/news/2014-07-30/ nrnweedzapping-daleks/5633014*].

Buhler, D.D., Liebman, M. and Obrycki, J. J. 2000. Theoretical and practical challenges to an IPM approach to weed management. *Weed Science*. **48**:274- 2280.

Chauhan, B.S. 2020. Grand Challenges in Weed Management. Frontier Agronomy. **1**:3. *doi: 10.3389/fagro.2019.00003.*

Christensen, S., Sogaard, H.T., Kudsk, P., Norremark, M., Lund, I., Nadimi, E.S. and Jorgensen, R. 2009. Site-specific weed technologies. *Weed Research*. **49**: 233–241.

Dabney, S.M., Delgado, A. and Reeves, D.W. 2001. Using winter cover crops to improve soil and water quality. *Commun. Soil Sci. Plant Anal*. **32**, 1221.

David, L. and Brown, R.B. 2001. Remote-sensing and mapping of weeds in crops. *Journal of Agricultural Engineering Research*. **78**: 117–125.

European Commission. 2019. Commission Implementing Regulation (EU) 2019/1100 of 27 June 2019 concerning the non-renewal of approval of the active substance desmedipham, in accordance with Regulation (EC) No 1107/2009 of the European Parliament and of the Council concerning the placing of plant protection products on the market, and amending the Annex to Commission Implementing Regulation (EU) No 540/2011.

European Commission. 2020. Communication from the Commission to the European Parliament, the Council, the European economic and social committee and the Committee of the regions. A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food sys- tem. 20.5.2020.

Eurostat. 2021. Organic farming statistics. Available at: *https://ec.europa.eu/eurostat/statistics-explained/index.php/Organic_farming_statistics*.

Fernandez-Quintanilla, C., Pena, J.M., Andujar, D., Dorado, J., Ribeiroand, A. and Lopez-Granados, F. 2018. Is the current state of the art of weed monitoring suitable for site-specific weed management in arable crops? *Weed Research*. **58**: 259– 272.

Gerhards, R. and Oebel, H. 2006. Practical experiences with a system for site-specific weed control in arable crops using real-time image analysis and GPS-controlled patch spraying. *Weed Research*. **46**: 185–193.

Gerhards, R., Sökefeld, M., Nabout, A., Therburg, R.D. and Kühbauch, W. 2002. Online weed control using digital image analysis. *Journal of Plant Diseases and Protection*. **18**: 421–427.

Gnanavel, I. 2015. Eco-Friendly Weed Control Options for Sustainable Agriculture. *Sci. Int.* 3: 37–47.

Hammermeister, A. 2016. Organic weed management in perennial fruits. *Sci. Hortic*. **208**: 28–42.

Hamouz, P., Hamouzova, K., Holec, J. and Tyser, L. 2013. Impact of site-specific weed management on herbicide savings and winter wheat yield. *Plant, Soil and Environment.* **59**(3): 101– 107.

Hartzler, R. and Buhler, D. 2007. Management of agricultural weeds. Ecologically Based Integrated Pest Management. In Opender KoulGerrit and W. Cuperus; CABI: Wallingford, UK, 2007; pp. 37–51. ISBN 9781845931636.

Hollick, V. 2014. Ladybird developer awarded research of the year. News page, 24 June 2014. The University of Sydney website. [*URL http:// sydney .edu.au/news/84.html? newsstoryid= 13686*].

ISAAA. 2019. Global Status of Commercialized Biotech/GM Crops in 2019. ISAAA Brief No. 55. ISAAA: Ithaca, NY.

Lancaster, S.R. 2021. Chemical Weed Control for Field Crops, Pastures, Rangeland, and Noncropland; Kansas State University: Manhattan, KS, USA, 2021; p. 148. Available online: *https://www.bookstore.ksre.ksu.edu/pubs/CHEMWEEDGUIDE*.

Lowenberg-DeBoer, J., Huang, I.Y., Grigoriadis, V. and Blackmore, S. 2020. Economics of robots and automation in field crop production. *Precision Agriculture*. **21**: 278–299.

Mia, M.J., Massetani, F., Murri, G. and Neri, D. 2020. Sustainable alternatives to chemicals for weed control in the orchard—A Review. *Hortic. Sci*. **47**: 1–12.

Monteiro, A. and Santos, S. 2022. Sustainable Approach to Weed Management: The Role of Precision Weed Management. *Agronomy.* **12**: 118. *https://doi.org/10.3390/agronomy12010118.*

MacLaren, C., Storkey, J. and Menegat, A. 2020. An ecological future for weed science to sustain crop production and the environment. A review. *Agron. Sustain. Dev*. **40**: 24.

Nukala, R., Panduru, K., Shields, A., Riordan, D., Doody, P. and Walsh, J. 2016. Internet of things: A review from farm to fork. 27th Irish Signals and Systems Conference (ISSC) (2016), pp. 1-6, DOI-10.1109/ISSC.2016.7528456.

Osten, W. and Cook, N. 2016. A review of technologies that can be enabled by robotics to improve weed control in Australian Cotton Farming Systems. Cotton Research and Development Corporation, Swarm Farm Robotics, Gindie, Queensland.

Pannacci, E., Lattanzi, B. and Tei, F. 2017. Non-chemical weed management strategies in minor crops: A review. *Crop. Prot*. **96**: 44–58.

Ribas, P. and Matsumura, A. 2009. The chemistry of pesticides: Impact on health and the environment. *Rev. Lib*.**10**: 149–158.

Peera, P., Debnath, S. and Maitra, S. 2020. Mulching: Materials, Advantages and Crop Production. In Protected Cultivation and Smart Agriculture; New Delhi Publishers: New Delhi, India, 2020; pp. 55–66.

Pérez-Ruíz, M., Slaughter, D.C., Fathallah, F.A., Gliever, C.J. and Miller, B.J. 2014. Co-robotic intra-row weed control system. *Biosystems Engineering*. **126**: 45–55.

Popay, I. and Field, R. 1996. Grazing Animals as Weed Control Agents. *Weed Technology*. **3**:12-20.

Perez, T. and Gonzalez, F. 2014. Agricultural robotics an outlook into a new generation of tools for site specific crop and weed management. pp. 52–59. In: Proceedings 17th Precision Agriculture Symposium of Australasia.

Rao, V.S. 2018. Principles of Weed Science (Third Edition). CBS Publishers and Distributors Pvt. Ltd. New Delhi, India.

Rao, V.S. 2021. Precision weed management-A means of boosting Agricultural productivity. *Indian Journal of Weed Science*. **53**(3):209-215.

Rueda-Ayala, V., Rasmussen, J. and Gerhards, R. 2020. Mechanical Weed Control. In Precision Crop Protection-the Challenge and Use of Heterogeneity; Oerke, E.C., Gerhards, R., Menz, G., Sikora, R., Eds.; Springer: Dordrecht, The Netherlands, 2020.

Santos Valle, S. and Kienzle, J. 2020. Agriculture 4.0—Agricultural Robotics and Automated Equipment for Sustainable Crop Production. In Integrated Crop Management; FAO: Rome, Italy, 2020; Volume 24, Available online: http://www.fao.org/3/cb2186en/CB218 6EN.

Scavo, A. and Mauromicale, G. 2020. Integrated Weed Management in Herbaceous Field Crops. *Agronomy*. **10**: 466.

Sims, B., Corsi, S., Gbehounou, G., Kienzle, J., Taguchi, M. and Friedrich, T. 2018. Sustainable Weed Management for Conservation Agriculture: Options for Smallholder Farmers. *Agriculture*. **8**:118.

Singh, V., Rana, A., Bishop, M., Filippi, A.M., Cope, D., Rajan, N. and Bagavathiannan, M. 2020. Chapter Three - Unmanned aircraft systems for precision weed detection and management: Prospects and challenges. *Advances in Agronomy*.**159**: 93– 134.

Sorensen, C.G., Madsen, N.A. and Jacobsen, B.H. 2005. Organic farming scenarios: operational analysis and costs of implementing innovative technologies. *Biosystems Engineering*. **91**: 127–137.

Sundmaeker, H., Verdouw, C., Wolfert, S. and Prez Freire, V. 2020. Internet of food and farm Digitising the Industry - Internet of Things Connecting Physical, Digital and Virtual Worlds, 2 (2016), pp. 129-151.

Swinton, S.M. 2005. Economics of site-specific weed management. *Weed Science*. **53**: 259–263.

Thorp, K.R. and Tian, L.F. 2004. A review on remote sensing of weeds in agriculture. *Precision Agriculture.* **5**: 477–508.

Wang, A.W., Wen, Z. and Wei, X. 2019. A review on weed detection using ground-based machine vision and image processing techniques. *Computers and Electronics in Agriculture.* **158**: 226–240.

Young, S., Pierce, J. 2014. Automation: The Future of Weed Control in Cropping Systems; Springer: Berlin/Heidelberg, Germany, 2014; pp. 249–259.