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# Precision weed management: A means of boosting agricultural productivity

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**ABSTRACT**

Weeds constitute a major constraint to agricultural productivity. Chemical weed management has been the focus in agriculture ever since the discovery of 2,4-D over 75 years ago. But repeated application of one type of herbicides will sort out resistant strains within the weed population. 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. Currently, 262 weed species (152 dicots and 110 monocots), infesting 93 crops and non-crop areas in 70 countries, have been identified to develop resistance to different herbicides. In this situation, weed scientists need to look for alternative weed management approaches that enhance agricultural productivity. 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.

## INTRODUCTION

### Chemical weed management

Weeds constitute a major constraint to global agricultural productivity. The era of chemical weed management with organic synthetic herbicides began with the introduction of 2,4-D, a phenoxy herbicide, in 1945. The discovery of 2,4-D was considered to be “greatest scientific discoveries of the 20$^{th}$ century (Fryer 1980). Its discovery and use was followed by substituted urea and triazine herbicides. Later, numerous other herbicide groups and herbicides over 350 were introduced during the next four decades. These were soon followed by numerous other herbicide groups over the next four decades. These herbicides have been considered the panacea for weed problems in agriculture, aquatics, forestry and non-cropping systems. Subsequently, these chemicals caught the attention of the farmers world over. These were considered viable alternatives for manual and mechanical methods.

The discovery of 2,4-D has also immediately impacted Indian agriculture. Since the initial testing in 1946, a number of herbicides have been tested for their efficacy against many weed species and utility in field crops (Mani 1977, Rao *et al.* 2014). Herbicide usage gained momentum in India since 1980s with their use in wheat followed by rice farmers in Punjab, Haryana and Uttar Pradesh.

Weed science turned a corner when glyphosate was made commercially available in1974. Glyphosate introduction created enormous enthusiasm in weed science community as farmers around the world began to use this broad-spectrum post-emergence herbicide to control a wide range of perennial weeds in croplands. It is also used in no-till and minimum-till farming. In India, glyphosate was introduced in 1980 in tea plantations, followed by other plantation crops and non-crop situations.

Five years after 2,4-D discovery, Blackman (1950) forewarned that forewarned that “repeated spraying with one type of herbicide will sort out resistant strains within the weed population.” This warning became reality when, in 1954, a report from U.K. revealed that continuous application of 2,4-D has led to resistance of weed species normally susceptible to it. This was followed by two other reports against 2,4-D in 1957, one from Hawaii where biotypes of *Commelina diffusa* in sugarcane fields (Hilton 1957), and another from Ontario, Canada, where biotypes of *Daucus carota* in sections of highway weeds (Switzer 1957) exhibited resistance. The extensive use of same group of herbicides has resulted in the development and evolution of herbicide resistant species of weeds, and herbicide resistance has become a significant global problem (Beckie *et al.* 2019).

Currently, 263 weed species (152 dicots and 111 monocots) infesting 95 crops and non-crop areas in 71 countries have been identified to develop resistance to 164 different herbicides belonging to 21 of the 31 known herbicide sites of action (Heap 2021). As several species showed resistance to herbicides of multiple sites of action, the number of unique resistant cases stood at 504 (species x sites of action). For example, *Lolium rigidum* is resistant to herbicides of 14 different sites of action. The other prominent ones include *Echinochloa crus-galli* var. *crus-galli* (10), *Poa annua* (9), *Eleusine indica* (8), *Lolium perenne* ssp. *multiflorum* (8), *Alopecurus myosuroides* (7), *Amaranthus palmeri* (7), *Amaranthus tuberculatus* (=*A. rudis*) (7), *Avena fatua* (7) and *Echinochloa colona* (7).

In India, only two species (*Phalaris minor* and *Rumex dentatus*) have been reported to be resistant to three groups of herbicides (ALS, ACCase and Photosystem II inhibitors) [Heap 2021]. However, farmers frequently report about the failure of herbicides in securing effective control of weeds. This was particularly true in the case of glyphosate which was being used for over 40 years, beginning with tea in 1978.

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.

Weed resistance to herbicides has led to the development of crops resistant to previously non-selective herbicides. Around 190 million hectare 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.

Several countries led by USA have widely adopted HR biotech crops, while India has been growing only the insect-resistant (IR) *Bt* cotton since 2002. With adoption of *Bt* varieties, the country has achieved a great stride in cotton production, accounting for a quarter of market share in global cotton production in 2017. Herbicide-resistant biotech crops are not approved in India, although they are reported to be grown illegally by farmers in key cotton-growing states (Yaduraju 2021).

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).

## 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.

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, 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.

**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.

**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).

**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.

**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.

**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, Swift 2015). 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.* (**Figure 1**) (Rao 2018).

**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.

**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.

**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.

**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.

**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.

**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.

**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).

**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

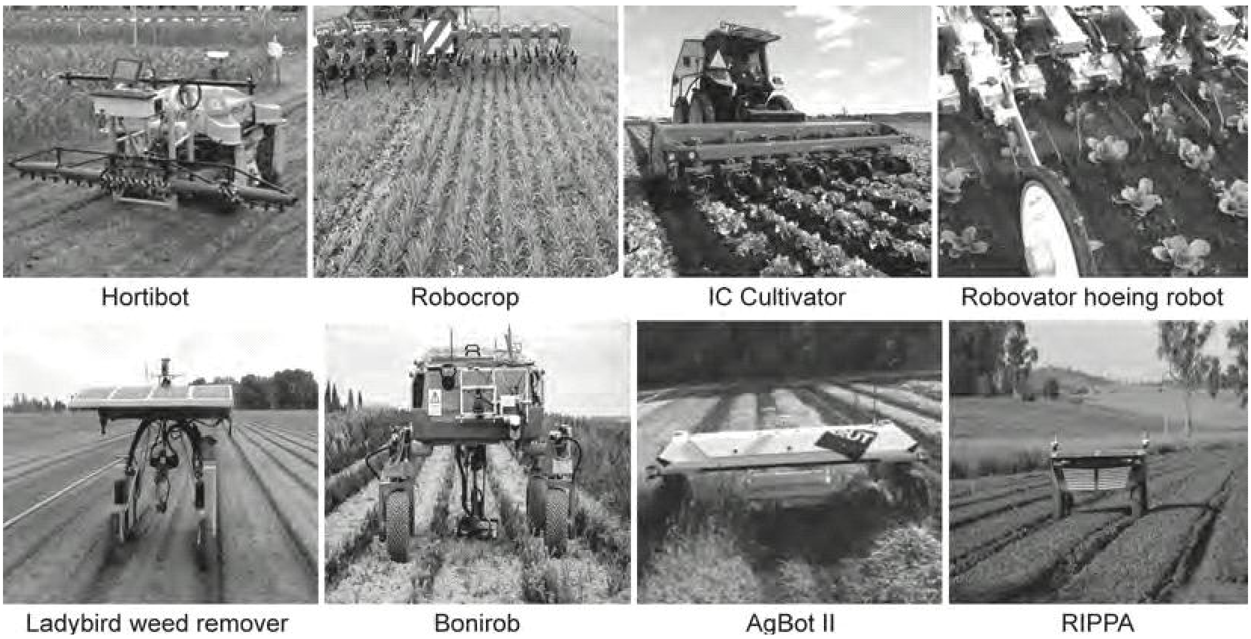


**Figure 1. Different robotic machines and systems developed and under development across the world** (Rao 2018). a) Hortibot: Piquepaille 2007; b) Robocrop: Tillett. 2008; c) IC Cultivator: Agri-Trade 2019; d). Robovator 2018; e). Ladybird Weed Remover: Underwood. 2016; Bonirob: Anonymous 2015; AgBot 11: Bryant 2014; RIPPA: Australian Centre for Field Robotics—University of Sydney)

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.

**AgBot**: Agribot is a light-weight, golf-buggy sized robot designed as an autonomous vehicle by Queensland University of Technology, Australia. The newer prototype AgBot 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, Agbot II which can reduce the costs of weeding crops by around 90%.

**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 h in one trip.

## INTEGRATED WEED MANAGEMENT

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, 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.

## NEXT GENERATION WEED SCIENTISTS

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.

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