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Possible solutions to manage herbicide-resistant weeds

With the increased incidences of herbicide-resistant weeds in South Africa and across the world, it is necessary to avoid management practices that will result in high selection pressure of resistant genotypes and subsequently increased gene frequencies.[1,2] Reducing overreliance on herbicides, preventing the spread of resistance, and reducing selection pressure by using a more diverse approach such as using integrated weed management (IWM) strategies is necessary. IWM is a holistic method of managing weeds that incorporates various weed-control techniques to provide crops an advantage over weeds.[3] These chemical, mechanical, biological, and cultural strategies will ensure the longevity of various modes of action across a wide range of cropping systems.[1,4]

Chemical management

Chemical weed control is dominated by the use of synthetic herbicides, but may also involve the use of bio-herbicides.[5] Herbicide rotations and sequential application of different herbicide mixtures are also useful strategies.[1] Recent studies have also shown that herbicide mixtures are unaffected by resistance.[6]

While herbicide combinations and rotations are useful tactics, there is a chance that multiple herbicides will concurrently lose their efficacy if they have similar modes of action. Furthermore, if two mixing partners have different propensities for selecting resistance, similar efficacy, persistence, soil residual activity, and are applied repeatedly they may facilitate multiple resistance.[7,8] Herbicide label guidelines should also be followed because applying less than the recommended rate (low doses) may cause the evolution of metabolic resistance. Equally so, overdosing should also be avoided as high herbicide doses eliminate susceptible populations quickly but result in a rapid build-up of resistant populations.[1,2,9] For this reason, chemical control needs to be used in combination with cultural, biological, and mechanical techniques.

Cultural management

Cultural weed management entails disrupting weed life cycles and altering weed communities by using cover crops, crop rotations, intercrops, and timing of weed control. Protective barriers are also necessary to prevent mechanisms from combining by limiting propagule distribution, pollen migration, and reproduction of resistant populations.[1] Because there is some relationship between temperature and the effectiveness of glyphosate[10] and glufosinate[11], timing of weed management may also be beneficial. Strategies can be developed such as spraying herbicides depending on the local climatic conditions.[12] For example, it is recommended that for *Eleusine indica* temperature forecast for the days after glyphosate treatment should be cooler.[13] In contrast, for *Ambrosia artemisiifolia* (common ragweed) and *Ambrosia trifida* (giant ragweed) it is recommended that the temperature should be at least 29 °C during the day for higher glyphosate efficacy.[14] This is consistent with Guo et al.[13] who observed that the efficacy of glyphosate varies depending on the type of weed species and the temperature. Sammons and Gaines[15] further stated that not all mechanisms of resistance are temperature sensitive, whereas, for glufosinate-ammonium, higher

temperatures and full sunlight are required on the day of application because day temperatures of 10 °C and below reduce glufosinate activity.[16]

Biological management

Biological management involves using living organisms or products from living organisms to control weeds. Biological management uses natural enemies of weeds such as herbivorous animals, pathogens, and insects.[17] Some weeds are naturally susceptible to pathogens. Weeds such as *Centaurea solstitialis* are susceptible to naturally occurring fungi.[18] Furthermore, Charudattan[18] examined a list of pathogens that can act as biocontrol agents against various weed species. As of 2020, 18 countries have approved the introduction of 36 fungal pathogens for the traditional biological management of weeds.[19] The limitation of biological management is that it is context-dependent, and implementing it may depend on a specific local agricultural environment.[17]

Mechanical management

Mechanical weed management is also referred to as physical weed management. It involves tillage and other thermal techniques.[5] In mechanical management, tillage is the most dominant weed control strategy.[17,20] Tillage may result in soil erosion and reduction in soil organic carbon. However, this is not to say that tillage is always undesirable because it can contribute to soil aeration and cause a reduction in nitrous oxide, but it needs to be used in combination with other weed management strategies outlined above.[20] Thermal weed control strategies including cryogenic, direct, and indirect heating were reviewed by Korres et al.[21] Similarly, examples of weed control strategies using artificial intelligence such as uncrewed aerial vehicles and robovotor were reviewed by Ghatrehsamani et al.[22]

Many IWM strategies only include chemical and physical or chemical and cultural strategies. These result in integrated herbicide management (IHM) disguised as IWM.[3] Furthermore, based on a recent study, it was argued that some of the techniques mentioned above are 'technological fixes' and that although IWM is a step in the right direction, it is also inadequate. The authors suggested ecological weed management (EWM).[20]

Ecological weed management

Ecological weed management is based on four principles: (1) increasing diversity, (2) reducing resources available to weeds, (3) using weak filters instead of consistent use of strong filters to avoid selection pressure, and (4) making use of the positive attributes of weeds.[20]

Increasing diversity in the farm can be achieved by using organic fertiliser, as inorganic fertiliser selects for dominant weed species with similar resource requirements as the crop[20], and the integration of legumes and livestock, as rotating crops with grazed legumes increases weed diversity. Weed diversity plays a role in increasing pollinators, thus improving bee health and subsequently increasing crop yields[20,23], whereas livestock can target palatable weed species. Grazing has also been reported to decrease *Palmer amaranth* by 75%.[24] As in IWM, EWM calls for tillage but reduced tillage.[20]

Intercropping not only plays a role in the first principle but also in the second principle. Intercropping reduces resources available to weeds. When intercrops are present, they capture light and nutrients which would otherwise be taken up by weeds.[25] Precision agriculture is defined as supplying only what the crop needs when needed; this is also a good way to starve weeds. This may be achieved through drip irrigation and fertigation.[20]

Avoiding strong filters, such as using herbicides unnecessarily, but using multiple weak or soft filters is desirable, especially when rotated between years. Examples are varying the planting dates and timing of weed management strategies and using mulches, perennial crops, and weed wipers.[20] In a study conducted in the Western Cape, it was observed that mowing in vineyards resulted in weed diversity. Furthermore, mowing promoted shorter weeds, which are considered less competitive with grape vines. In contrast, herbicide applications to control weeds on vineyard floors selected for tall weeds with decreased diversity.[26]

Lastly, the fourth principle involves taking advantage of the positive attributes of weeds. This is undoubtedly overlooked because weeds are always seen as enemies. However, weeds play various essential ecological functions.[20,27] Soybean is usually grown for its protein content. It was shown that weed competition increases the protein content of soybean from 0.7% to 1%.[28] In a systematic review conducted in 2018, it was also observed that weeds increase soil fertility and pollinator abundance and play a role in pest control, thus increasing crop yields.[27] Leaving weeds to grow in areas where there are no crops is also advised to allow weeds to provide other ecosystem services.

There are similarities between IWM and EWM; both advocate for tillage, cover crops, intercrops, diversifying control techniques, etc. This may be because some studies consider EWM a part of IWM.[5] In fact, when IWM was originally introduced in the 1980s, EWM was mentioned as part of IWM.[29] Nonetheless, fully adopting EWM will not be an easy task without help from other stakeholders because farmers might only adopt EWM after seeing it successfully implemented in their own or similar farming environments. Therefore, weed scientists have a crucial role to play, and they can do so by carrying out pilot experiments.[20]

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