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Prospects of ecological weed management

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Abstract
Weeds are an important constraint in agricultural production systems causing economic losses. Introduction of herbicides as a means of weed control in 1940s was one of the major approach for intensification of agricultural production systems. Sooner, chemical weed control rapidly evolved as standard approach, making other management options for regulating weed population size far less important. Continuous use of herbicides resulted in greater selection pressure within the plant community leading to weed shift and evolution of herbicide tolerant species. Globally, there are currently 505 unique cases of herbicide resistant weeds (Heap, 2019). Due to longer persistence, they pose an impact on soil pH, microbial activity, surface and underground water resources polluting the environment. Considering these ill effects and increased interest in organic agriculture, alternative solutions have evolved. As options for biological control are limited and complete reliance on mechanical control is undesirable, ecological based weed management (EWM) which works proactively with nature's operating system is an option in the forefront. In line with EWM, there is a need to change the way in which we think about weeds and its management, moving beyond the long standing reactive approach in which weed management is an afterthought. Under such situation, optimizing agro-ecosystem design criteria to manage weeds becomes a long term investment that yields measurable dividends. With the three principles namely reduction of weed seedling emergence, improved crop competitiveness and reduced weed seed bank size, EWM is a possible solution where cropping systems are designed to lower weed community densities and improve crop competitiveness.

Keywords: Ecology, herbicides, resistance, weeds and weed management

Introduction
Man has replaced natural ecosystems by a controlled system of cropping or management, the species previously adapted to the area disappear and others which find the environment favorable to them invade the site. Weeds are the "camp followers" of crops. Acting at the same trophic level as the crop, weeds capture a part of the available resources that are essential for plant growth. Weed biology, ecology and physiology does not differ from plant biology apart from the notion that the plants under investigation are considered to be "unwanted". Weeds are an important constraint in agricultural production systems. Introduction of herbicidal control in the 1940s was one of the major triggers of the intensification of agricultural production systems, most notably characterized by a tremendous increase in labour-productivity. For this reason, chemical weed control rapidly evolved into the standard approach, making other management options for regulating weed population size far less important. Finally, the increased interest in organic agriculture calls for alternative non chemical weed management solutions. As options for biological control are limited, a complete reliance on mechanical control is undesirable and herbicidal control is prohibited, ecological weed management seems particularly relevant.

Methods of weed control
The different weed control strategies are cultural, mechanical, biological and chemical control measures. With the classical approach being less suitable for controlling weeds in cropping systems, more emphasis was put on the bioherbicide approach. Although the efforts resulted in commercial registration of some products, bioherbicides never managed to occupy a sizeable share of the market. One problem has been that the reliability of field efficacy is not at levels comparable with that of herbicides. Another option is mechanical weed control where the technologies for controlling weeds in the crop row are also present. Still, the strong dependency

on weather conditions, as well as the damage to soil structure associated with frequent application of mechanical control makes a heavy reliance on this technology undesirable. The heavy reliance on chemical weed control is nowadays considered objectionable. This is first because a heavy reliance implies extensive use of compounds and genetically modified crops with a potential negative side-effect on food safety, public health and the environment. Second, cropping systems with a narrow focus on herbicidal control are becoming increasingly vulnerable, as herbicide resistance and stricter regulations with regard to herbicides are frequently creating situations where part of the weed community can no longer be controlled by chemical means.

A study was conducted by Bhutada *et al.*, 2015 [4] at Akola, Maharashtra, during rabi season in clay loam soils to know the effect of herbicides and cultural practices on soil microbial population in chickpea. Before and after spraying of herbicides the samples were drawn for microbial study and it was observed that before spraying of herbicide the bacterial, fungal and actinomycetes count were more or less similar. After spraying of herbicide microbial count was reduced in herbicidal treatment than cultural method of weed control treatment.

Need for non chemical weed management tools

There are 505 unique cases (species x site of action) of herbicide resistant weeds globally. 259 species (151 dicots and 108 monocots) of weeds developed resistance for 167 different herbicides. Among the different sites of action known, weeds have evolved resistance to 23 of the 26 known herbicide sites of action of which, ALS inhibitors occupy the first position. Herbicide resistant weeds have been reported in 93 crops in 70 countries (Heap, 2019) [8]. Hence, non chemical weed management tools are to be considered due to

- Rapidly increasing herbicide resistance
- Environmental impacts
- Growing consumer concern about herbicide and other pesticide residues in food and the environment
- Growth of organic agriculture which prohibits the use of xenobiotic materials as inputs into farming systems.

Laws of ecology in relation to weed management

In 1971, as the negative impacts of human technologies on the biosphere were becoming increasingly visible, the ecologist Dr. Barry Commoner in his book 'The Closing Circle: Nature, Man and Technology, described several 'Laws of Ecology' to provide guidelines in resolving questions about tradeoffs inherent to technology adoption and implementation. These laws are correlated to weed management options by Bagavathiannan and Davis, 2018 [1] as below:

Everything is connected to everything else: As per this law of ecology, interdependence of biotic and abiotic factors systems helps recognizing weed management as part of an overall system which leads to development proactive measures rather than depending on set of control methods to keep the weed growth in check.

Everything must go somewhere: Enhanced resource capture at the farm scale is very important in achieving effective ecological weed management through increasing competitiveness for crop.

Everything is always changing –The change in abiotic environment over time influencing biological organization dynamics calls for improving the successional complexity of agricultural systems.

There is no such thing as a free lunch: The cost of losing herbicidal technology to resistance is alarming and sustainability of such various technologies must be considered as a long-term investment rather than an afterthought.

Everything has limits: Global resources are finite. The longevity of these resources requires meticulous planning and implementation by developing truly multi-tactic approaches.

Ecological weed management

A combination of methods aimed to achieve long-term weed suppression through the use of ecological interactions between crop, weeds, soil and/or other taxa fostered by appropriate agro-ecosystem management, with the least possible use of direct weed control methods, either chemical or non chemical." (Paolo Barberi, 2019) [13]. It is referred as "many little hammer approach". Attacking ecological weak points of weeds during field operations, crop season and crop rotation can minimize the weed problem considerably which is the main strategy of EWM.

The term "ecological weed management" was first explicitly used in a book named Ecological management of agricultural weeds by Liebman *et al.*, 2001 [10], who intended it as "weed management procedures that rely on manipulations of ecological conditions and relationships."

Bastiaans *et al.*, 2008 [3] identified ecological weed management with cultural weed control, *i.e.*, "any adjustment or modification to the general management of the crop or cropping systems that contributes to the regulation of weed populations and reduces the negative impact of weeds on crop production which involves the tactical and strategic level of decision making."

Ecological *vs* Integrated weed management

EWM does not include direct weed control methods, *i.e.*, the in-crop application of chemical or non-chemical (mechanical, thermal, biological) methods that are deliberately used by farmers to eliminate weeds during crop growing cycle (Bastiaans *et al.*, 2008) [3]. Although the objective of EWM is to reduce recourse to direct weed control methods, it is undeniable that they are and will continue to be an important component of integrated weed management (IWM). To design an agroecosystem that is less vulnerable to weed interference, by integrating all possible means of control (agronomic, genetic, biological, physical, and chemical) but with a main emphasis on prevention. As such, IWM and EWM look very similar, and arguably the main difference is that EWM (Bastiaans *et al.*, 2008) [3] does not include direct weed control methods.

Mechanisms or principles of ecological weed management

Reduction of weed seedling emergence

A number of options arise for hindering the weed seedling emergence from soil weed seed bank. Photo control is one such option. Seeds of many annual weed species require a light-stimulus to trigger germination. Consequently, night-time soil cultivation or covering tillage-equipment with black plastic or non-light transmitting cloth has regularly been investigated as a means to reduce weed emergence. After germination, the seeds initially rely on the energy stored in the endosperm. Consequently, successful emergence depends on factors like soil compaction, burial depth and seed size. Mulching increases the physical barrier that has to be overcome by the germinated seeds and is therefore another means to achieve a reduced establishment of weed plants. For mulches consisting of decaying fresh plant material, the release of allelochemicals strengthens the inhibitory effects on weed seed germination and early growth.

Mahmood *et al.*, 2015 [11] conducted a field study in silt loam soils at Pakistan to evaluate the influence of different crop residues (sorghum, sunflower, rice and maize) as surface mulch on weed dynamics and productivity of maize. The dominant weed species observed were Purple nutsedge (*Cyperus rotundus* L.), horse purslane (*Trianthema portulacastrum* L.), Barnyard grass (*Echinochloa colonum* L.) and Bermuda grass (*Cynodon dactylon* L.). Among different mulching combinations, rice + sunflower + maize @ 6 t ha^{-1} each recorded maximum reduction in density and dry biomass of horse purslane (8.97 /0.25 m^2 and 13.03 g/0.25 m^2) and purple nut sedge (7.33 /0.25 m^2 and 5.30 g/0.25 m^2), respectively, as compared to weedy check. The extent of total weeds suppression by this mulch combination was almost similar with pre-emergence herbicidal application of s-metolachlor + atrazine @ 1.08 kg a.i. ha^{-1} suggesting that crop mulches can be successfully employed in ecological weed management programmes

Imtiyaz Hussain *et al*., 2017 [9] conducted an experiment to know the allelopathic potential of sesame plant leachate against *Cyperus rotundus* L. where the leaves of 2 months old sesamum plants were harvested and soaked in distilled water (DW) in the ratio of 1:4 for 48 h at room temperature. DW was added in the leachate to maintain original volume of water and it was treated as mother leachate of 100 per cent and stored at 10 °C to avoid biodegradation. The leachate was diluted with DW to prepare leachate of 50 per cent concentration. Petriplates are filled with sand to study the sprouting which was irrigated with leachate of 10 ml of respective concentration and with DW taken for control. Iron pots filled with 2 kg sieved garden soil mixed with farm yard manure in ratio of 4:1 to study the full growth. There are substantial difference between tubers sprouting and shoots length of treated and untreated plants. Number of tubers germinated and length of shoots in treatments significantly decreased compared to control. The sesame leachate decreased the plant height, number of leaves and caused hindrance in leaf promotion. The leachate (100%) was most inhibitory to plant height. The allelopathic leachate showed a significantly inhibition on formation of new bulb. New bulbs were not formed at higher concentration both 20 and 40 DAS. In control, plants with tubers, root and shoots, rhizomes and new bulbs are present while in W50 plants with tubers, root and shoots, few rhizomes and single bulb present while in W100 plants with tubers, root and shoots present but only with few rhizomes and devoid of new bulb. The results revealed a decrease in chl a, chl b, and carotenoid content in treated plants. A maximum 45, 57, and 73 per cent reduction of chl a, chl b and carotenoid content respectively, was recorded in plants under concentration of leachate with highest treatment at 40 DAS. In transverse section of purple nut sedge rhizome vascular bundles (VB) are loosely distributed around the perimeter of central pith and shown a significant difference in numbers. The number of VB decreased with the increased concentration of the leachate.

Das and Yaduraju, 2008 [6] conducted a study in sandy loam soils at IARI to know the effect of soil solarization and crop husbandry practices on weed species competition and dynamics in soybean-wheat cropping system. A transparent polyethene film (100 µ thick) was used in the soil solarization plots and was installed in the second fortnight of May. In the summer cowpea for fodder treatment was sown in the first week of May and was harvested as fodder just before sowing of soybean in the first fortnight of July. Wheat straw @ 6.0 t ha^{-1} was incorporated at the second fortnight of May almost one and half months before sowing of soybean under wheat straw incorporation treatment. Among crop husbandry practices, wheat straw incorporation brought about a significant reduction in *Cyperus rotundus* population and soil solarization in *Cynodon dactylon* population at 20 DAS in soybean. Dicot weed population, on the contrary, was significantly lower in soil solarization than in wheat straw incorporation and the other treatments remained at par with solarization. Similarly, total (monocot + dicot) weed population was lowest in soil solarization and differed significantly with others. Therefore, it can be adopted in soybean wheat cropping system to exhaust weed seed bank in soil for better weed management.

Improved crop competitiveness

Competitive relations between crop and weed plants don't just rely on species characteristics. Relative time of emergence, for instance, is an important determinant of competitive ability, as an early emergence generates an improved access to the available resources. Selection of the largest seeds and seed priming are some means of providing crop plants a favourable starting position. Transplanting is one means to establish the desired initial size differences between crops and weed plants. Row placement of fertilizers can also be used to improve the relative competitive ability of crop plants. In this case, rather than a temporal advantage, crop plants are favoured by creating a spatial advantage in resource accessibility. Apart from increasing the competitive ability at the individual plant level, improved competitiveness of the crop can also be gained from modifications at the population level. An increased seeding rate is an obvious example of this. In addition, the weed suppressing ability of a weakly competitive crop canopy can be increased by the addition of a more competitive second crop like inter crops or live mulches.

A study conducted by Manjanagouda, 2018 [12] during *kharif* 2016 and *summer* 2017 to know the effect of weed management practices in paired row maize based intercropping system revealed that intercropping of maize + cowpea has recorded lower dry weight of grasses (24.95 g m^{-2}), sedges (12.60 g m^{-2}), broad leaved weeds (60.08 g m^{-2}) and weed index (17.67%) as compared to intercropping with field bean or pole bean in red sandy loam soils at Bengaluru, Karnataka. Weed dry matter accumulation in intercropping systems may be attributed to shading effect and competition stress created by the canopy of more number of crops in a unit area having suppressive effect on associated weeds, thus preventing the weeds to attain full growth and providing the crop advantage over weeds. The major weed flora of the plot was BLW- *Borreria hispida, Commelina benghalensis, Euphorbia geniculata, Gomphrina decumbens, Parthenium hysterophorus* and *Portulaca oleraceae.* Grasses - *Brachiarea reptens, Chloris barbata, Cynadon dactylon, Dactyloctenium aegyptium, Digitaria marginata and Eleusine indica.* Sedges - *Cyperus rotundus.*

Paudel *et al*., 2017 [14] reported that transplanted rice with two hand weedings (25 and 50 DAT) has lowest weed biomass as compared to direct seeded rice. Among the different cultivars tested, US-382 recorded lower weed number and higher yield at Nepal. The transplanting has lowest weed biomass because of water level to suppress the weed species and higher yield of US-382 is due to large crop canopy, high tillering, high fertilizer sensitive, less shattering effect and reduced weed growth. The major weeds found in the field were Belautijhar (*Rotata indica*), Jwanejhar (*Fimbristylis miliacea*), Mothejhar (*Cyperus iria*), Pirlejhar (*Polygonum barbatum*), Gandhe (*Ageratum conyzoides*) and Dubo (*Cynadon dactylon*).

Field experiments conducted by Chauhan and Johnson (2011) [5] at IRRI, Philippines on effect of row spacing on yield of aerobic rice. *Rottboellia cochinchinensis*, *Digitaria ciliaris*, *E. colona*, and *Eleusine indica*. *Ageratum conyzoides*, *Amaranthus spinosus*, *A. viridis*, *Commelina benghalensis*, *Corchorus olitorius*, *Cyperus iria*, *C. rotundus*, *Dactyloctenium aegyptium*, *Eclipta prostrata*, *Portulaca oleracea*, and *Trianthema portulacastrum* were other species common during both seasons. Among different row spacings (15 cm, 10-20-10 cm and 30 cm) tried, 15 cm row spacing recorded lower weed biomass (150 and 294 g m^{-2}) and higher rice grain yield (2059 and 2437 kg ha^{-1}) during wet (WS) and dry seasons (DS), respectively, as compared to 30 cm row spacing. While, weed growth and grain yields were similar between 15 cm and 10–20–10-cm row spacing in loamy soils suggesting that rapid canopy closure could suppress weed growth effectively. The duration of the weed-free period required to prevent a particular level of yield loss would be greatest with 30-cm rows. In 15-cm rows, for example, 95 per cent of maximum yield would result from controlling weeds until 52 DAS in the wet season and until 56 DAS in the dry season, whereas this level of yields in the 30-cm rows were achieved when weeds controlled until 58 DAS in the WS and 64 DAS in the DS. This is because of optimum seeding rate and rapid canopy closure could further suppress weed growth and reduce the required critical weed-free period.

Shahzad *et al*., 2016 [16] conducted an experiment at Pakistan in silty clay soils where five tillage systems *viz*. zero tillage (ZT), conventional tillage (CT), deep tillage (DT), bed sowing (60/30 cm with four rows; BS1) and bed sowing (90/45 cm with six rows; BS2) were evaluated in five different crop rotations *viz*. fallow-wheat (FW), rice-wheat (RW), cotton-wheat (CW), mungbean-wheat (MW) and sorghum-wheat (SW) for their effect on weed infestation and productivity of bread wheat. The un-disturbed soils (ZT) under fallow-wheat or mungbean-wheat rotations favoured the weed prevalence (a total weed dry biomass of 72.4-109.6 and 105.6-112.1 g m^{-2} in first and second year, respectively). Contrary to this, the disturbed soils (CT, DT, BS1 and BS2) had less weed infestation with either of the rotations (a total weed biomass of 0.4-7.1 and 1.1-5.4 g m^{-2} in first and second year, respectively). Sorghum-wheat rotation had strong suppressive effect on weed infestation in all tillage systems. The possible reasons may be the use of crop sequence that creates varying patterns of resource competition, allelopathic interference, soil disturbance, and mechanical damage, which eventually results in unstable and frequently inhospitable environment for proliferation of a weed species.

Robert *et al*., 2004 [15] conducted an experiment at Canada in sandy clay loam soils to know the effect of nitrogen fertilizer application method on weed growth in spring wheat. A dose of 50 kg ha^{-1} of N in the form of ammonium nitrate was chosen. Nitrogen application treatments were consisted of granular ammonium nitrate applied broadcast on the soil surface, banded 10 cm deep between every crop row, banded 10 cm deep between every second crop row, or point-injected liquid ammonium nitrate placed between every second crop row at 20-cm intervals and 10 cm deep. The major weeds noted were *Setaria viridis* (green foxtail), *Avena fatua* L. (wild oat), *Chenopodium album* L. (common lambs quarters) and *Brassica kaber* (wild mustard). As nitrogen fertilizer has been documented in breaking dormancy of certain weed species, densities of wild oat and common lambs quarters often were greater with surface broadcast N than with sub surface N applications. Point injection of N fertilizer recorded lower density and biomass of weeds as the localized placement increases the crop competitiveness and reduced weed growth.

The experiments, conducted by Bastiaans *et al.*, 2008 [3] at IRRI, 40 aerobic/upland genotypes, including *indica*, *japonica*, *aus* and mixed types of *Oryza sativa* were used. Growing these genotypes in the presence of weeds revealed a large variability in weed-suppressive ability (WSA) among genotypes. Among the different germplasm groups, *indica* and *aus* germplasm appeared to be more weed-suppressive than *japonica* germplasm. The indica group combined weed-suppressive ability with a strong yielding ability. Both under weed-free and weedy conditions the average grain yield was significantly higher than that of the other groups. The *aus* group showed the lowest yield reduction, which apart from its strong WSA might hint at a high level of weed tolerance. These findings indicate that *indica* and *aus* are likely to be the most suitable gene donors for improvement of WSA in aerobic rice in tropical regions.

Reduced weed seed bank size

Surface layers of the soil are the store houses of the weed seeds. Depletion of this weed seed bank can be obtained by increasing the losses (output), by reducing the input or through a combination of both. Predation, decay and germination are the main processes that contribute to a reduction in seed bank size. Seed predation has been recognized as an important means of seed mortality, particularly in the period following seed shed. Use of no-till systems and delaying post-harvest tillage operations extend the period during which the seeds are exposed to seed predators. Seed predator numbers may be enhanced by creating better opportunities for shelter and additional food. Processes like microbial decay are the cause of the remaining vulnerability of seeds after burial. So far, the relation between microbial activity and microbial composition of the soil and seed decay is poorly understood. Seeds also leave the seed bank through germination. Fatal germination can be regarded as the main mechanism behind the use of stale seedbeds. By creating an additional time lapse between seedbed preparation and seeding, the first weed flush can be easily controlled. Restricting the production of new seeds is another option. As competition is a mutual interaction between plants, improving the competitive ability of the crop not only diminishes crop yield reduction but also results in reduced weed seed production. Crop rotation is another important factor, as it improves diversity and prevents the development of a weed population that is perfectly tuned with the growing cycle of a particular crop.

Seed bank losses can be occurred by seed predation (manipulation of agricultural habitats as to attract predators e.g., no-till, stubble cultivation), seed decay and increased germination - false and stale seedbed techniques.

Gallandt *et al.*, 2005 [7] conducted a four year rotation based experiment on effect of consecutive and alternate years of cover crops (red clover) on the activity as well as density of *Harpalus rufipes* (major weed seed predator) and seed predation of six weed species (velvet leaf, wild mustard, yellow foxtail, common lambs quarters, redroot pigweed, and hairy galinsoga) in vegetable based cropping system. There was a greater density of *H. rufipes* in red clover vegetated plots, particularly, in the two year consecutive cover crop system whereas weed seed predation was higher in the alternate year cover crop system at USA. Predation was positively correlated with the activity density in one of the 2 years of cover crop.

Singh and Singh (2012) [17] during *kharif* season studied the effect of methods of rice establishment and weed management practices in irrigated direct seeded rice and noted that dry seeded paddy after stale bed using shallow tillage recorded lower density and biomass of sedges (11.7 m^{-2} and 4.9 g m^{-2}) and

Echinocloa colonum (249.6 m^{-2} and 143.5 g m^{-2}), respectively, as compared to dry seeded rice after stale bed using glyphosate in sandy clay loam soils of Varanasi, Uttar Pradesh.

Agro-ecosystem services from ecological weed management

- Enhanced soil fertility and crop yield benefits
- Biological pest control
- Improved land productivity and economics
- Increased resource use efficiency
- Management of herbicide resistance

Conclusion

Ecological weed management is a proactive approach which is in line with the natural processes. Accordingly, we have use our greater understanding of weed ecology and design our cropping systems that integrate diversity, improving crop competiveness and increasing weed seed bank losses. In this concept, practices such as photo control and mulching can reduce weed seedling emergence. Further, increasing seeding rate, transplanting, localized input application, competitive genotypes, intercropping and live mulches can improve crop competitiveness over weeds and various seed bank losses contribute to reduced weed seed bank thus proving EWM an effective non-chemical option for weed management.

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