Integrated Weed Management Practices for Adoption in the Tropics

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Additional information is available at the end of the chapter

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1. Introduction

The earth is undergoing a number of irreversible changes as a result of the activities of man, many of which are adversely affecting the environment. Inappropriate methods of agricultural production, especially those stimulated by efforts in pursuit of short-term gains, have been identified as prime contributors to this environmental degradation.

In earlier times, traditional farming in the tropics involved the use of natural resources in adequate quantity for the sustenance of its population, without diminishing the natural resource base. Key elements of that system included multiple cropping and mixed farming, minimum tillage and water conservation techniques, the use of simple hand tools and other low input technologies.

These sustainable farming methods have been described in pejorative terms as drudgery, laborious, and inefficient. Many have been rejected and new technologies and other high energy based inputs have been embraced. These technologies are costly and heavily foreign-exchange dependent. They also disturb the delicate ecological balance resulting in increased occurrence of pests and diseases, shift in noxious weed populations, soil erosion and pollution of the air and water resources.

The situation in the tropical world is exacerbated as many tropical countries are characterised by conditions that are ideal for the prolific growth and development of a range of plant species. Many of these species are generally non-harmful. However, when inappropriate methods of weed control and/or poor crop management strategies are employed, weeds assume noxious potentials. Ready examples are corn grass (*Rottboellia cochinchinensis*), white-top (*Parthenium hysterophorus*) and nutgrass (*Cyperus rotundus*) [33].

Present farming involves substantial reliance on a range of manufactured inputs. The high dependence on herbicides for weed control in the cultivation of rice, maize, bananas, citrus, sugarcane, onions, white potatoes and vegetable crops is not unnoticed. The competition among suppliers of herbicides has resulted in lower costs of these products which has fuelled their use and abuse in the region.

Low-input, sustainable agriculture addresses multiple objectives from increasing profits to maintaining the environment, and builds on multiple systems as integrated pest management (IPM), integrated weed management (IWM), and crop rotation. Integrated weed management involves the combination of a number of weed control practices that reduces the dependence on any one type of control method and also lowers the input of herbicides. This approach is important for the control of perennial weeds that are inadequately controlled by any single method [8]. The application of IWM also includes the knowledge of past annual and perennial weed populations in fields and weed seed bank [7], competitive crop cultivars, improved crop and soil management practices, and appropriate selection of herbicides [52]. In the context of sustainable agriculture, the concept of IWM seems enlightening and applicable.

The objective of this paper is to discuss the various weed management practices for the control of noxious weeds in major cereal, root and vegetable crops in tropical sustainable agriculture and the strategies used over time to promote their adoption by small farmers.

1.1. Common Integrated Weed Management (IWM) strategies in the tropics

Integrated weed management systems are based on an agro-ecosystem approach for the management and control of weeds at economic threshold levels [12]. Many farmers in the tropics today practise the same weed control measures as was practised before the introduction of herbicides [35]. The IWM systems approach includes any or a combination of the following practices that give a crop a comparative advantage in competing with weeds.

1.1.1. Prevention strategies

Prevention strategies include field sanitation and harvesting methods that do not spread weed seeds and vegetative propagules at every step of production (such as seed selection, field preparation, planting, fertilization, irrigation, weed control, harvest and transport) [19]. Such strategies can significantly reduce the infestation of noxious weeds such as nutgrass and white-top [7]. The use of clean crop seed, especially those direct seeded, e.g., maize and legumes, is critical in the prevention of weed problems in new and existing fields. Prevention should be a daily activity, incorporated into the routine of all workers involved in agricultural production, at farm, state and national levels [19]. It is recommended that managers make simple, cost effective modifications to their farm practices to mitigate the risk of introducing new weed seeds to the field. Some of the key considerations as outlined in [19] include:

- diligent monitoring for sources of new weed introductions to the agro-ecosystem;
- proactive government laws and regulations controlling the introduction and movement of plant materials or soil from one location to another;

- destroying vegetative propagules of perennial weeds;
- whenever possible, depleting the soil weed seed bank;
- propagating seeds and seedling transplants in media free of weed propagules;
- preventing weeds from going to seed in crop fields;
- cleaning farm machinery before movement into fields;
- minimizing the presence of weed seed in livestock feed, manures and composts;
- preventing weed seed introduction into rivers and irrigation canals.

For preventive strategies to be fully adopted in an IWM approach, there must be an attitudinal change by farmers and agricultural educators in the tropics. Prevention, although complex, is a very efficient technique for any property size at all crop production stages, from the acquisition of machinery, seed, water and fertilizers, to crop harvest and processing.

1.1.2. Competitive crops and/or smother crops

Crops differ in their competitiveness with weeds based on their emergence, leaf-area expansion, light interception, canopy architecture, leaf-angle, shape and competitiveness. Within a crop species, cultivars may vary in their competitiveness. While the improved varieties may be high yielding, the traditional varieties exhibit multiple adaptations, competitive ability against weeds and require less agricultural input. The use of competitive crops to discourage weeds is an important IWM strategy. To maximise crop production by minimising the impact of weeds, replacement series and addition series designs have been recommended for intercrop, cover crop and green manure selection [41].

Plant height and leaf area index correlate with competitive ability in row crops. These characters allow the crop to outgrow and cover the weeds. Indeterminate varieties of bean, cowpea, squash and cucumber appear to be better competitive than determinate varieties [38, 39]. The indeterminate varieties of these crops have a vining or spreading habit which allows rapid canopy closure, thus suppressing emerging weeds.

Some plants are able to exude chemical substances which suppress the growth of other neighbouring plants. Research in plants with allelopathic potential is ongoing and has revealed a clearer understanding into the genetics of allelopathic activity in certain crops [29].

Smother crops are quickly established and usurp the resources that weeds would otherwise use. The suppression of weeds may be through both competition (resources) and allelopathy [11]. Smother crops include cowpea (*Vigna unguiculata)*, forage soya beans (*Glycine max* L.Merril), Sudan grass (*Sorghum bicolor* subsp. *drummondii*), kudzu (*Pueraria phaseoloides*) and pumpkins (*Cucurbita maxima*), which are very effective in suppressing nutgrass (*Cyperus rotundus*) and small broadleaved weeds.

1.1.3. Optimum plant population

Row spacing and seeding rate may influence the ability of the crop to compete with weeds for resources and, therefore, may affect weed management [24, 45]. The rapid closure of the crop canopy can be obtained with a reduction in row spacing [1], an increase in seeding rate [42], and selection of varieties with traits that favour rapid canopy development [13]. It has been reported that rows of 38 cm or less could increase yields and reduce tillage and herbicide requirements because of faster canopy closure [1]. Cereal and vegetable crops can compete with weed growth if they are established at the optimum plant population that allows them to more effectively usurp resources. If crops can reduce incident light by 50 % or more, weeds will seldom become a problem [6, 15]. This approach requires closer intra-and interrow spacings and higher crop densities than normally used.

1.1.4. Cover crops and mulches

Cover crops have long been used extensively in the tropics for soil and water conservation, to maintain soil structure and enhance soil fertility, especially on steep or difficult terrain. They are often referred to as living mulches. The use of leguminous cover plants to suppress weeds in plantation crops in the tropical world dates back many decades, but the integration of the legumes into arable cropping systems has not been developed to a level acceptable to farmers. Cover crops also contribute to pest management and help to suppress unwanted weeds. Its use has been mainly in plantation crops. The introduction of inexpensive nitrogen fertilizers and herbicides encouraged many farmers to discontinue this practice. Cover crops can be intercropped or interplanted with a crop of economic significance. They work by excluding light and limiting weed emergence. Examples of cover crops in the tropics include: *Mucuna pruriens* (L.) DC. (velvet beans), *Desmodium heterocarpon* var *ovalifolium* and *Arachis pintoi* Crap. & Greg. (wild or perennial peanut).

Mulches, on the other hand, may be in the natural form of plant or crop residues or in synthetic form as plastic films or woven synthetic fibres. Other non-living mulches can be either natural materials (plant leaves, stalks, straw, compost and dry soil) or synthetic materials, such as polyethylene, which are used widely in pineapple production. The major disadvantages of plastic films are material costs and difficulty in removal after cropping season. Organic mulches or living mulches are considered cover crops, e.g., mungbean (*Vigna radiata* (L.) Wilczek cv. Local) and have been shown to be an economical alternative to synthetic mulches [36]. Watermelon and tomato farmers in Dominica, West Indies use Guinea grass (*Panicum fasiculatum*) as a mulch and cover crop. The grass is killed using a weed killer such as paraquat, and when it re-grows, it is brush-cut before crop emergence or otherwise left as a residue. The crop is planted directly into the cover crop residue which enhances soil and water conservation and protection from wind.

In root crops, for example cassava, live green legumes e.g. *Desmodium heterophyllum* (Willd) DC [20] with bean *(Phaseolus* sp.) have been used successfully. Both legumes gave better weed control and crop yields than the herbicide and mulch treatments and *Desmodium heterocarpon* var *ovalifolium* in banana [25]. *Stylosanthes guianensis* (Aubl.) SW, too, has been used as a cover crop to suppress weeds in cassava [43, 44]. Legume and dry mulch covers are beneficial because they improve soil organic matter and nutrient status, prevent erosion and suppress weeds [30]. The use of legume covers is, however, expensive because of the cost of seeds and labour for their establishment [53, 56]. It is important to use legume and other crop covers which will not compete with the crop for resources. Moreover, any crop cover used must directly benefit the farmer if adoption of the practice is to be sustained.

Some of the weed species that are easily smothered by live legume covers include: *Ageratum conyzoides* L., *Alternenthera sessilis* L. R. Br. ex Roth, *Mimosa invisa* Mart, *Digitaria orizontalis* Willd, and *Panicum maximum* Jacq. However, some sedges and grasses like *Cyperus rotundus* L (purple nutsedge), *Rottboellia cochinchinensis* (Lour) Clayton (Raoul grass), *Sorghum halepense* L. Pers (Johnson grass) and *Ipomoea* sp. (morning glory) are noxious weeds and difficult to control in root and cereal crops [20, 46].

Both cover crops and mulches offer great agro-ecological potential. They serve as a physical barrier against weed emergence, both conserve the soil and improve the ecological balance of the soil, enhance crop yield and provide several environmental services. These new technologies, however, are not easily accepted by small farmers in the tropics. Notwithstanding, they offer a complex combination of interrelated practices which include: (i) necessary practices so as to ensure the production and retention of sufficient mulch and (ii) complementary practices in order to be able to grow a crop and/or maintain yield levels. This typically implies several adaptations to the entire farm production system. Whether mulching actually is a viable component for smallholder conservation farming in developing countries depends on a number of factors, including bio-physical, technological, farm level and institutional factors. The combination of these factors determines the feasibility of and the economic returns to mulching practices—and thereby farmer acceptance.

The development and dissemination of cover crops and mulches for small farmers in tropical developing countries highlights a number of promising experiences, particularly among banana growers i in St. Vincent, in the Caribbean [25]. The technology offers significant savings through reduced tillage and alleviation of some major crop production constraints such as water conservation, timeliness of land preparation and crop establishment.

1.1.5. Improved husbandry

The basic principles of IWM which include: suppression of weed growth, prevention or suppression of weed seed production, reduction in weed seed bank and prevention or reduction in weed spread, are key elements of all improved husbandry practices. All crop husbandry practices, particularly precision placement and timing of fertiliser application, enhance maximum stimulation of the crop and minimum stimulation of the weed population. Additionally, the use of clean certified seeds, clean farm implements, effective seedbed preparation and seeding methods that improve crop growth, all reduce weed competition [7, 36]. Other management practices including: cultural weed control (intercropping, early planting, optimum plant crop density, and tillage), chemical (minimum herbicide) weed control, mechanical weed control and hoe weeding, have been shown to reduce the competitive effects of weeds on vegetable and cereal crops growth, development and yield [36].

Weeds have a life cycle synchronised to that of the crop such that more weeds emerge with the crop with the onset of rains [33]. Intermittent wetting and drying of weed seeds brought about by early rains preceded by dry spells break seed dormancy [8]. Tillage operations bring buried weed seeds to the surface where they germinate. However, early planting of the crop gives the crop a competitive advantage over the weeds [33, 35].

1.1.6. Irrigation practices

Judicious irrigation practices such as the use of clean water, channels and canals, can reduce the spread of weed seeds to uninfested fields [3, 38]. Flooding is an important component of weed management in rice in the tropical world. In irrigated and flooded systems, the environment in which weed seeds have to germinate is characterized by the existence of low oxygen concentrations. Differential responses between rice and weeds to flooding could be an important component of weed management for the direct-seeded rice crop, since rice is tolerant to flooding, but many weeds, e.g., *Cyperus iria, Fimbristylis miliacea, Leptochloa chinensis, Ludwigia hyssopifolia* and similar weed species are not. However, the timing, duration, and depth of flooding and intensity and frequency of irrigation are critical if germination and growth of a number of weed species are to be effectively suppressed.

Irrigated and upland rice and cereal crops are typically grown with few agricultural inputs. A wide range of weeds infest upland rice, many of which are pan-tropical, including the grass weeds: *Digitaria* spp., *Echinochloa colona*, *Eleusine indica*, *Paspalum* spp., and *Rottboellia cochinchinensis*, and the broadleaf weeds: *Commelina* spp., *Ageratum conyzoides*, *Portulaca oleracea*, *Amaranthus* spp. and *Euphorbia* spp. The variability of weed species composition in upland rice tends to be greater than in the other production systems, and is dependent upon the ecology the cropping system and the management practices used.

Once weed seedlings have emerged and passed the seedling stage, their growth will not be reduced by flooding. In an irrigated environment, there was no emergence of *Leptochloa chinensis* when rice was flooded 5 days after seeding, but its emergence increased to more than 70 plants m^{-2} when flooding was delayed until 20 days after seeding. In such situations where water is not readily available, early flooding would make the best use of water to control weeds. Introducing flooding after herbicide application or weeding or hoeing could help reduce future weed growth and the need for additional interventions [17, 27].

1.1.7. Inter-row cultivation and minimum tillage

Inter-row cultivation is practical in widely spaced row crops, such as maize, vegetables, sugarcane and banana [8, 19], which have interrow distances of 60 cm or more. Interrow cultivations are done by tractor drawn implements or hand operated rotary tillers. The efficiency of this method is higher than manual methods. Minimum tillage, on the other hand, involves the use of the minimum amount of tillage required for crop production for meeting the tillage requirement under existing soil and climatic conditions [56]. It refers to eliminating excess tillage, e.g., reducing four secondary tillage steps to two [8]. Both operations complement and enhance the efficiency of minimum herbicide input through soil incorporation of pre-plant herbicides.

Successive inter-row cultivation has been effective in reducing weed growth and density. Many weed species exhibit morphological plasticity in response to environmental variation and density. Weeds can compensate for density changes so that total biomass per unit area is held relatively constant. Inter-row cultivation improved crop yield by 33% and 78% [20]. However, herbicide application resulted in yield increases of 57 to 300% [27]. Benefits from inter-row cultivation can be limited by in-row weed growth. Most uncontrolled weed growth occurs in the uncultivated area adjacent to and within the crop row. Therefore, the integration of other mechanical or cultural methods often improves with inter-row cultivation. Inter-row cultivation also has potential as a means of controlling late flushes of weeds, but it should not be considered a stand-alone weed management technique since significant in-row weed growth may limit benefits [7].

Tillage operations have a major impact on distribution of weeds in the soil, weed survival and persistency [8, 10], weed species diversity in a given cropping system [15] and the selection pressure on the weed population. Although not much research has gone into the effect that tillage has on tropical weeds, studies have shown that grass weeds, *Setaria* spp and *Corchorus tridens* were higher under the ripper and basins compared to conventional tillage. Also, broadleaf weeds were less in minimum tillage compared to conventional tillage. Rotation with conventional tillage systems controls the grasses and perennials but other weeds or weed groups may assume numerical dominance. To balance the pressure of tillage, there may be need to consider rotational tillage where appropriate [35].

Tillage affects vertical weed seed distribution in a soil profile and this seed distribution affects weed seed germination by influencing the soil environment surrounding the seeds [12, 13]. There is less soil disturbance with minimum or zero-till systems and, as such, most of the weed seeds are on or near the soil surface after crop planting. In systems with high soil disturbance using conventional tillage, mixing weed seeds uniformly in the tilled-soil depth has been found to be beneficial. It was also found that on direct-seeded rice, 77% of the weed seeds were retained in the top 2 cm soil layer under a zero-till system, whereas soil disturbance under a conventional tillage system resulted in 62% of the seeds being buried to a depth of 2-5 cm. The seeds were not present in the 5-10 cm soil layer in the zero-till system [22, 23].

The conditions for seed germination are conducive near the soil surface and therefore there is high germination of the weed seeds that are close to the soil surface under zero-till systems, for example, *Ageratum conyzoides*, *Eclipta prostrata, Echinochloa colona, Digitaria ciliaris* and *Portulaca oleracea*. The weed seed populations on the top that are not dormant are easily destroyed by the stale seedbed practice. In this practice, weed seeds are allowed to germinate after a light irrigation or shower and are then killed by using a non-selective herbicide or shallow tillage. This practice helps to reduce the size of the weed seed bank in the soil [8]. Conservation agriculture, or zero tillage farming, is an effective solution to stopping agricultural land degradation, for rehabilitation, and sustainable crop production intensification in the tropics [21, 22].

1.1.8. Minimum herbicides

Herbicide use continues to be one of the most important tools in weed management. However, an IWM approach creates an opportunity to reduce herbicide rates and in some instances, just forgo the use of herbicides altogether.

Given the high cost of herbicides in the tropics, smallholders sometimes either reduce the herbicide rate or mix with other herbicides with differing modes of action. These practices are not without risk. Oftentimes, smallholders realise that these practices are inconsequential and there is no recourse with pesticide retail outlets regarding poor herbicide performance if label rates have not been followed. Yet, farmers often cut rates as a cost saving strategy.

The effectiveness of a reduced rate usually depends on the type of herbicide, weed species present, weed pressure, environmental conditions and, of course, the competitiveness of the crop stand. If the weed pressure is high or the weeds are under stress, it is probably advisable to use an integrated approach. However, reduced rates of herbicide may lead to some level of herbicide resistance and thus the approach to be taken must be carefully considered.

The extent of herbicide use in the tropics is closely related to the cost and availability of labour. Large scale rice and banana production in the tropics receive more than two herbicide applications. However, in the smaller farms, only about 50% of the rice area is treated, particularly where rural labour is available. Herbicides replace hand weeding and enable direct seeding which is less labour demanding, compared to transplanting. Herbicides are also used in the transplanted systems, though to a much lesser extent, and in systems particularly where crop rotation is practised.

There is a need to reduce herbicide input in crop production which can complement cultural practices. With proper timing and selected application methods, good control may be achieved with one-fourth to one-half rates of application [7]. Herbicides are becoming more expensive, and by reducing the pesticide load into the environment, the risk of pollution is reduced. This can be achieved by:

i. banded application of herbicides

ii. the use of low volumes to improve glyphosate performance

iii. proper timing of post emergence herbicides

iv. the use of herbicide combinations at low rates

v. the use of newer, more active and more rapidly degradable herbicides, and

vi. monitoring fields to achieve spray decisions

Using lower herbicide dosages would reduce expenditure on herbicides to a fraction of the cost of full label herbicide rates while maintaining efficacy and other benefits derived from herbicide use. Research has revealed that half the recommended dosages of atrazine and nicosulfuron resulted in the lowest weed biomass. Mixing a third of the recommended herbicides of Atrazine and Nicosulfuron resulted in equivalent weed control to the atrazine label recommended dosages. Weed seed production was reduced. Reduced herbicide dosages

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may fit into the economics of the small farmer and hence has the potential to be a 'small hammer' in the IWM programme [51]. However, as mentioned before because of the risk of herbicide resistance, this decision must be taken carefully.

1.1.9. Crop and herbicide rotation

Crop and herbicide rotation reduce selection pressure on weeds and this allows for the development of resistant ecotypes and biotypes [35]. Crop rotation should include crops with either different cultural practices or morphology that will upset the life cycle of weeds as in white-top (*Partheniuim hysterophorous*) and corn grass (*R. cochininensis*) [7, 33]. Crop rotations and crop diversification are useful tools for weed management, as they encourage operational diversity that in turn can facilitate improved weed management [31]. Manipulating different planting and harvesting dates among crops provides more opportunities for producers to prevent either plant establishment or seed production by weeds. If sufficient differences exist in the germination requirements of crops and weeds, then seed date can be manipulated to the benefit of the crop for example. Weeds then germinate after canopy closure and they become non competitive [35].

However, in the small farm production systems, crop diversification in rotation and even crop succession are limited. The effectiveness of crop rotation in weed suppression may be enhanced by crop sequences that create varying patterns of resource competition, allelopathy, soil disturbance and mechanical damage to certain species. Diversified crop rotations are likely to provide best opportunities for exploiting diverse sets of tactics and ecological processes to suppress weeds [57]

There are only eight modes of action in available herbicides, and as a consequence rotating herbicides is as important as alternating crops, as overuse will increase the risk of single-, cross-, and multiple resistance [29].There is also the potential for a "species shift," as new weed species take over when the population of another diminishes, as a result of an effective herbicide or other control practice. Resistance, however, poses a more serious problem, as it depends on the weed species, the efficacy of the herbicide, and the frequency of herbicide use. Continuous use of a particular herbicide will contribute to resistance, and farmers should rotate two or three herbicides [49]. Additionally, using herbicides with the same mode of action will create an environment for resistance development. To reduce the risk of resistance the following guidelines should be considered:

- Alternate non-chemical with chemical control methods.
- Rotate herbicides, including mode of action of herbicides with the same site of action. Example, Maverick is a sulfonylurea herbicide and Pursuit is an imidazolinone herbicide, but both are group 2 herbicides.
- Tank mix different modes of action to apply different types of materials.
- Rotate crops which differ in their competitiveness against weeds based on life cycle, growth habit, maturity length, etc., so rotating to different crops can help prevent some weed species

from becoming dominant in a given field and control "suspect" herbicide-resistant weeds as if they were an invasive weed species.

Multiple management practices can be used in an integrated plan to prevent or delay the development of herbicide-resistant weed populations. In addition, avoid using herbicides with the same site of action in both fallow years and in the succession crops. Herbicide diversification is the key to preventing resistance, since using one system will create resistant weeds. Herbicide rotation is critical to maintaining grade and delaying resistance. Rotating herbicides with multiple modes of action is critical to delaying the spread of resistance and preventing weeds and volunteers [27].

Currently, there is an increase in the number of resistant weed biotypes, including those resistant to glyphosate, PPO, ALS, dicamba and triazine chemistries. The rapid growth of Respect the Rotation™ is a testament to the urgency with which thousands of growers treat the issue of weed resistance [36]. Glyphosate-resistant weeds are spreading at alarming rates from rampant infestations; 358 biotypes have developed resistance to one or more herbicide groups, including glyphosate, PPO, ALS, dicamba and triazine chemistries.

1.1.10. Intercropping or relay cropping

Intercropping or relay cropping systems are based on the principle that space should be occupied by crops and not weeds [57]. Relay cropping can be practised by market gardeners who harvest their crops by hand. These crops should be planted in such a way that the intercrop provides an effective canopy to shade weeds, or that previous crop residue can be used as a mulch to prevent weed growth in successional crops, e.g., pigeon pea (*Cajanus cajan*) interplanted with maize (*Zea mays*). Occasionally, the second crop in some intercropping systems is for the purpose of weed management. Crops such as velvetbean (*Mucuna pruriens*), lablab (*Lablab purpureus*), *Desmodium heterocarpon* and tropical kudzu (*Pueraria phaseoloides*) have been used successfully as intercrops in banana (*Musa* sp.), cassava (*Manihot esculenta*) and maize for the management of weeds such as watergrass (*Commelina* sp.) and cogongrass (*Imperata cylindrica*) [18, 25, 26] across tropical environments. It was found that intercrops may inhibit weeds by limiting resource capture by weeds or through allelopathic interactions [31], and that weed biomass was reduced in 90 % of the cases when a main crop was intercropped with a "smother" crop. It has also been reported that self-regenerating intercrops reduce establishment costs and can provide weed suppression over years [37].

1.1.11. Biological agents

The use of biological agents such as mycoherbicides, insects and pathogens to control weeds in the tropics is not common. However, the potential for its application to control noxious weeds using monophagous/oligophagous natural enemies must not be overlooked [29]. Table 1.0 shows some of the most successful achievements using this method of control which include: water hyacinth (*Eichhornia crassipes* (Mart.) Solms) using specific insects, white-top (*Parthenium hysterophorus* L.) using a fungus, Christmas bush (*Chromolaena odorata* (L.) King & Robins) using an insect and nutgrass (*Cyperus* spp.) using a fungus.

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Classical biological control is the best among the viable options available for sustainable management of invasive weeds, especially where other technologies such as chemical and mechanical control are unacceptable due to cost and adverse impact on the environment [40].

Some of the techniques described for biological control of weeds in developed countries can be safely and efficiently transferred to developing countries with minimal expense for the initial institutional and human-capacity building. It is essential to know the organism to be used as well as the methods for rearing and release and its host range in order to avoid problems with crops. *The Code of Conduct for the Import and Release of Exotic Biological Control Agents* (FAO, 1996), gives good guidance on how to proceed in order to introduce new exotic organisms for biological control.

Weeds	Biological control agents
Eichhornia crassipes (Mart.) Solms Water hyacinth	Weevils: *Neochetina eichhorniae*, *N. Bruchi* Moth: *Sameodes albigutalis*
Parthenium hysterophorus L. White-top	Fungus: *Puccinia abrupta* var. Partheniicola Zygogramma bicolorata Epiblema strenuana
Chromolaena odorata (L.) King & Robins. Christmas bush	Moth: *Parauchaetes pseudoinsulata*
Lantana camara L. Black sage, Lantana	Lacebug: *Teleonemia scrupulosa*
Cyperus rotundus L. Nutgrass	Fungus: *Puccina canaliculata* Dactylaria higginsii Moth: Bactra spp.
Amaranthus spp.	Fungus: *Phomopsis amaranthicola*
Rottboellia cochinchinensis (Lour.) Corn grass	Fungus: *Sporisorium ophiuri*
Adapted from: [29]	

Table 1. Some organisms used for the biological control of selected weeds

2. Adoption strategies

The traditional top-down approaches, participatory approaches and discovery based teaching methods have all been used to promote integrated weed management.

The top-down method has been by far the most predominant method and widely used in training on weeds and their control. The focus of these sessions was to train farmers how to apply, mostly synthetic pesticides, and emphasised the need for continuous application.

Farmers responded well to these instructional approaches given the severe losses they sustain because of the extent and vigour of weed growth in the tropics and the quick, highly visible effect of synthetic herbicide applications. These class and field sessions have been historically conducted either as stand-alone modules in training courses or as part of the general agronomic practices for field crops. Over the years, extension agents conducted these courses in communities or at centralised farmer training centres. The concept of integrated weed management was not part of the landscape at this time.

In the 1990s, the emergence of farmer participatory approaches to educating farmers gained momentum. Although the focus was on Integrated Pest Management (IPM), weed management was incorporated into learning activities. Farmers, for the first time, were presented with the option of applying a mix of weed management strategies instead of a single chemical option. The aim of farmer participatory approaches is to strengthen farmers' decision-making skills through an understanding of the agro-ecology of their fields. The approach is widely recognised as an integral part of more sustainable and environmentally friendly crop production practices. The flagship method, Farmer Field Schools (FFS), continues to be used as the preferred approach to integrated management mostly of pests and diseases but increasingly included is the management of noxious weeds.

The Farmer Field School approach involved farmers in activities mostly in the field to understand weed dynamics and to involve farmers in decisions to manage weeds using more sustainable approaches. These activities, done on farmers' fields, have been conducted across the Caribbean as part of the FFS approach to integrated pest management. Farmers have been exposed to different weed management strategies which stressed integrated approaches. FFS have been conducted in St Lucia, Suriname, Trinidad and Dominica [4].

The FFS model is flexible, and, in recent times, one component has been singled out for increased use because of the enhanced learning it provides. Discovery-based learning is based on the principles of experiential learning; farmers are guided by a trained facilitator who draws out their knowledge and helps them construct meanings based on their rich field experiences. This has been done in several countries of the Caribbean. Discovery-based learning activities have been used in St Vincent in a Farmer Participatory Research (FPR) process to manage weeds in bananas [25, 26]. Farmers were encouraged to plant several cover crops on their farms to evaluate the efficacy of these crops on weed control in bananas. As farmers carried out these activities, they took the weekly measurements and did simple statistical analysis. They were able to discover for themselves the benefits of alternative approaches to the pesticide approach both for their health and that of consumers in foreign countries who purchase their bananas.

Farmers in Trinidad have also conducted community experiments using paper, used cartons, grass much, plastic, precision irrigation all in an attempt to evaluate alternative weed management strategies. Farmers have discovered for themselves the effects of the various treatments and some of these have been adopted by farmers who are tending to move to the low pesticide/ organic farming methods.

A mix of adoption strategies has been used over the years in an effort to get the right approach to IWM. No silver bullet has been found. It is a work in progress. Given the diverse weed flora,

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farming experiences and farmer circumstances in the tropical world, scientists, educators and farmers will have to dedicate increased energies towards finding an approach that is economical, culturally acceptable and environment friendly.

3. Research needs for integrated weed management systems for the tropics

There is a need to encompass weed management into improved/integrated crop management systems and to develop research and development programmes that will facilitate a more comprehensive understanding of ecology, physiology, biochemistry, competitiveness/allelopathic potential and threshold of weeds.

4. Conclusion

The key to a successful weed management programme is the effective insertion into crop management programmes of those control techniques that will minimise the impacts of weeds not controlled by the competing crop. The dependence on overly generalized and increasingly expensive chemical input packages, developed elsewhere under a different set of conditions, and aggressively promoted by Researchers, Extension agents and Agro-chemical companies, must be broken.

The IWM systems approach fits into the work habit of many farmers and gives more effective control than when only chemical methods are used. In addition, yield improvements in the order of 40 to 100 % are realized. While IWM systems are considered technologically sound, the social and environmental advantages, as well as the economic costs associated with the practice, need to be ascertained. If farmers are not convinced of the economic viability of the system, then the technology no matter how sound will not be adopted.

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