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Economic threshold concept for weed management in crops: Usefulness and limitation

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ABSTRACT

The economic threshold (ET) is one of the major decision-making frameworks for rationalizing herbicides use for better weed management while reducing environmental impacts. The ET is the density of weeds at which the cost of control equals the benefits obtained under particular weed control measure adopted. The ET rejects complete eradication of weeds, but advocates regulating weed populations at economically optimum levels. Control measure is adopted only when weed competition goes beyond a certain limit, thus, it uses certain damage levels for making cost-efficient weed management decisions. Several decision-making models on ET are available with high to low degree of precision. Despite potentials, the adoption of ET models as the major criterion for cost-effective herbicide use has been low. Limitations are building up of seed bank by residual weeds, complexity in estimating ET density, patchy weed distribution, and limited validity in cropping systems with multiple weed species. Yet, the ET-based decision has great potential in designing weed management under single weed dominance in crops. Information on weeds population dynamics in cropping system, biology, ecology and spatial heterogeneity would make determination of ET more precise and reliable, and managing weeds using integrated approach more successful.

INTRODUCTION

Weed management has been primarily focused on selective herbicides since the inception of herbicides. But, the indiscriminate and increasing trend in herbicides use is a primary concern in present agriculture. Excess consumption of herbicides can be reduced by making rational decisions on weed management (Das *et al.* 2010). Making appropriate decision on the use of herbicides requires development of weed management decision models (Coble and Mortensen 1992). The development of weed management decision models is possible by through determining the ET of weeds, which assesses whether a treatment against weeds is necessary and economical (Cousens *et al.* 1986, Cousens 1987, Wilkerson *et al.* 2002). The ET concept is the principal guideline of pest/weed management that largely avoids eradication of pest(s) to regulate their populations at economically optimum levels (Coble and Mortensen 1992, Wilkerson *et al.* 2002, Das *et al.* 2014a). The ET for weed control or the "break-even point" is the level of weed infestation at which the cost of weed control operations is equal to the benefits obtained as a result of controlling the weeds (Cousens 1987, Hazra *et al.* 2011). Thus, the ET is primarily a binary decision-making concept ('control' or 'not control') that justifies adoption of control measures (Auld *et al.* 1987) or decides the weed density at which weed control becomes economically worthwhile (Cousens *et al.* 1988).

The ET concept was first introduced by Stern *et al.* (1959) and was defined as "the density at which control measures should be adopted to prevent an increasing pest population from reaching the economic injury level (EIL)." The EIL represents "the lowest population density of pests that can cause economic damage to crops." Stern *et al.* (1959) opined that the ET should be lower than the EIL, which provides sufficient time for the control measures to take action before the population reaches EIL. Initially, entomologists adopted ET in the early 1970s (Stern 1973, Wilkerson *et al.* 2002). Weed scientists adopted this later as the decision-making tool/ process for weed management. Coble and Mortensen (1992) and Thornton and Fawcett (1993) reported that this concept was the basis of majority of weed management decision models available to farmers. The ET-based weed management may lead to rationalization of herbicide use, which can reduce herbicide cost and environmental pollution while maintaining farm profitability (Swanton and Weise 1991, Jones and Medd 2000, Thomas *et al.* 2011). Besides, Norris (1992) opined that the ET-based concept can reduce future weed populations by reducing weed seed rain through control measure adopted when there is above-ET weed density. But, there may be chance of carry-over effect of the sub-ET weed density (when no control measure adopted) on weed seed bank over the years. However, most ET research, being a short-term approach, has overlooked this. Several competition thresholds, *viz*., period threshold, quantity threshold, damage threshold, economic threshold, action threshold, ecological threshold (Coble and Mortensen 1992, Das 2008) have been used for managing pests. Some of these thresholds can be applied to weed science for managing weeds in crops.

Determination of economic threshold (ET)

Determining ETs or action thresholds of weeds involves methods that can measure and predict the level of weed infestation. The level of weed infestation can be quantified in terms of weed population per unit area (Cousens 1985a, Cousens 1985b), relative leaf area *i.e*., proportion of leaf area of a weed species to the total leaf area of that weed and crop (Kropff and Spitters 1991, Kropff and Lotz 1993, Lotz *et al.* 1996), per cent ground cover of broad-leaved weeds (Gerowitt and Heitefuss 1990) or biomass of weeds. However, quantifying weed density for use in decision models by far has been the most common approach and simplest of all (Marra and Carlson 1983, Cousens 1987, Gerowitt and Heitefuss 1990, Coble and Mortensen 1992, Mortensen *et al.* 1993, Swinton and King 1994, Wilkerson *et al.* 2002). Usually, the density per unit area or relative leaf area of an individual weed is used in equations to predict yield loss. The gain or loss in crop values is generally estimated in terms of increase or decrease in crop yields. A weed-crop model developed across cropping systems can predict yield loss due to weeds or yield gain as a result of managing weeds. There are multiple simulation models available for this and for working out ET of weeds.

Economic threshold based on density-yield model

The relationship between crop yield/yield loss and weed density is worked out using a non-linear regression model derived from a rectangular hyperbola (**Eq. 1, Table 1**) (Cousens 1985a, Cousens 1985b, Norris 1999). The data and fitted curves are presented in terms of per cent yield loss using Eq. 2 (**Table 1**). This equation serves as the basis of many other models developed for ET calculation. A quadratic equation (**Eq. 3**; **Table 1**) is used for determining the ETs of different weed species based on their respective weed density (Cousens 1987).

Economic threshold based on yield-relative leaf area model

The empirical model (**Eq. 4; Table 1**), which relates crop yield loss to early observation on relative leaf area (*i.e.* proportion of leaf area of a weed species to the total leaf area of that weed and crop) can also be used to evaluate crop yield loss owing to weed density (Kropff and Spitters 1991, Kropff and Lotz 1993).

Economic thresholds based on other models

Economic threshold can also be derived from other models and empirical equations and a brief account of those models has been given in Eq.5 to Eq.15 (**Table 1**). These models have been successful in simulating crop yields and/or yield losses in concurrence with that of the observed field values.

Economic thresholds using crop yield loss

The ET based on economics of Cussans *et al.* (1986) and Cousens (1987) provides baseline information for making weed control decisions and plays a role for setting up an integrated weed management. However, several researchers have also estimated the ET of a weed considering its densities and threshold yield reduction (≤10%) without using models. For this, a relationship between weed density and crop yield was established using linear equation (Moorthy and Das 1998) or exponential equation (Sinha *et al.* 2009). Then, a weed density causing ≤10% yield loss was considered as the ET of that weed. This ET, however, is not much reliable since it does not consider other factors of production except the yield loss. Besides, the threshold yield reduction of ≤10% considered in these cases is not accepted across situations/sites. To mention, the farmers of the developed countries with high technical skills, and having access to improved methods of weed control, *e.g.*, herbicides may not allow losing 10% yield or even lesser reduction than this. The reverse may be true to the farmers of the developing countries, operating with low technical skills and less/no improved methods to whom even a 10% yield loss may be acceptable or is of usual occurrence.

Economic threshold research and applications

Experiments have been conducted across the globe (Mamun *et al.* 2013a, 2013b, Das *et al.* 2014b,

Table 1. Different models used for predicting economic threshold of weeds

SN	Model	Reference
1.	**Yield simulation using rectangular non-linear hyperbolic regression model:** $Y = Ywf\left[1 - \frac{id}{100\left(1 + \frac{id}{A}\right)}\right]$ ……(1) Percent yield loss (Y_L) $Y_L = \frac{id}{\left(1 + \frac{id}{A}\right)}$ …...(2) where, Y = observed yield; Ywf = estimated weed-free crop yield; i = percent yield loss per unit density as density (d) approaches to zero; and A = the asymptotic value of maximum yield loss in percent as density (d) approaches to infinity	Cousens (1985a, 1985b)
2.	**ET of weeds determination by using the quadratic equation:** $1 + (i/A)\,[2 - H - (YPAH/C)]T + (i/A)^2\,(1 - H)T^2 = 0$ …...(3) Where, Y = weed-free yield; P = unit price of produce; H = efficiency of herbicide; C = cost of weed control; T = economic threshold density; I and A values as per Eq. 2	Cousens (1987)
3.	**Empirical model to relate crop yield loss to relative leaf area of weeds:** $Y_L = \frac{qLw}{1 + (q - 1)Lw}$ …...(4) Where, Y_L = relative yield loss; Lw = relative leaf area of weed (i.e., leaf area of weed divided by the total leaf area of crop and weed per unit area); q = relative damage coefficient	Kropff and Spitters (1991), Kropff and Lotz (1993)
4.	Proportion of yield lost: $Y = ad^b$ …...(5) Yield: $y = y_{wf}\,(1 - ad^b)$ ……(6) Where, y_{wf} = weed-free crop yield; d = weed density; a, b = arbitrary parameters	Marraand Carlson (1983)
5.	**Certainty model:** $ET = \frac{Ca + Ch}{Lw \times Ps \times Hc}$ ……(7) Where, ET = economic threshold (number of weeds/l0 row meters); Ca = herbicide application cost per ha including labour and machinery costs; Ch = herbicide cost per ha for recommended dose; Lw = yield loss (kg/ha) per equidistantly spaced weed per 10 m of crop row; Ps = price of crop per kg; Hc = expected percent control with the given herbicide dose	Marraand Carlson (1983)
6.	$ET = \frac{Ch + Ca}{Ywf \times P \times L \times H}$ …...(8) Where Ch = herbicide cost (Rs/ha); Ca = herbicide application cost (Rs/ha); Ywf = weed-free crop yield (t/ha); P = price per unit of crop (Rs/t); L = proportional loss per unit weed density; H = herbicide efficacy (a proportional reduction in weed density by herbicide treatment)	Cousens (1987)
7.	**Step 1:** $y = \frac{(HM + UM)}{(OV \times UF)} \times 100$ …...(9) where, y = % yield loss associated with weed density (m^2); OV= average of expected maximum grain yield in weed-free plots (kg/ha); UF = price of grain (Rs/kg), HM= cost of herbicide (Rs/ha); and UM= application costs (Rs/ha) **Step 2:** Value of economic threshold is quantified by calculating y in the above equation and then replacing in a linear regression model, Y = a + bX where, Y = % loss of yield according to density in m^2, X = number of weeds in m^2 (economic threshold), b = regression coefficient	Uygur *et al.* (1999)
8.	$ET = \frac{Cc}{\left[R \times P \times \left(\frac{i}{100}\right) \times \left(\frac{H}{100}\right)\right]}$ ……(10) Where, ET= economic threshold (weeds/m^2), Cc=cost of control per ha (herbicide and application cost); R= yield (ton/ha); P = price of produce per tonne; i = yield losses (%) per unit of weed when the value of the variable approaches zero (Eq. 2); H = herbicide efficiency (%)	Lindquist and Kropff (1996)
9.	**Break-even yield loss (BEyl):** $BEyl = 100 - \left[\frac{YP - H}{YP}\right] \times 100$ ……(11) **Marketable break-even yield loss level (MBEyl):** $MBEyl = 100 - \left[\frac{YP - (H - Q)}{YP}\right] \times 100$ ……(12) Where, Y = predicted weed-free crop yield (t/ha), P= expected price of produce per ha, and H = price of herbicide per ha; Q = cost associated with dockage and drying of grains per ha	Weaver (1991)
10.	**Step 1:** Step 1 involves estimation of predicted crop yield (Y) based on Eq. 1. **Step 2:** $ET = \left[\frac{1 - (CP - H)/CP}{(r - s) + s\,\{(CP - H)/CP\}}\right]$ ……(13) Where, ET = economic threshold weed density (weeds/m^2); C = expected weed-free crop yield (ton/ha); P = crop price (Rs/ton); H= herbicide and application cost (Rs/ton); r = i/100 and s = i/A (values of i and A as per Eq. 1)	O'Donovan (1991)
11.	ET = Gain threshold/ Regression coefficient ……(14) where, gain threshold = cost of weed control (herbicide and application cost) per unit price of produce, and regression coefficient is the outcome of a simple linear relationship between yield (Y) and weed density/ biomass (x), Y = a + bx	Stone and Pedigo (1972)
12.	$Y = [\{(100/He \times Hc) + Ac\}/(Gp \times Yg)] \times 100$ ……(15) Where, Y = percent yield losses at a weed density; He = herbicide efficiency; Hc = herbicide cost; Ac= herbicide application cost; Gp = grain price and Yg = weed-free crop yield	Uygur and Mennan (1995)

Westendorff *et al.* 2014, Li *et al.* 2016, Tironi *et al.* 2016, Mehmood *et al.* 2018, Du *et al.* 2019, Galon *et al.* 2019, Raj *et al.* 2020) for determining ET values of weed species and predicting yield losses using various decision models to facilitate easier weed management decisions. A model usually describes the crop yield and/or yield loss as a function of weed competition (Cousens 1985a).The concept of thresholds has been successfully implemented by developing certain computer-based economic decision models or software. An effective decision model should take economics as well as biological factors into account, *viz.* nature of weed populations existing in the field, expected crop yield loss due to weed interference and potential economic returns for each control measure (Wilkerson *et al.* 2002). Thus, these decision models enable the growers in prior determination of economic and other effects of any weed control decision, and provide more efficient, reliable, and precise weed control (Coble and Mortensen 1992). A number of computerized decision-aid models (**Table 2**) available across the globe can help making weed management decisions by predicting yield losses due to weeds interference. These models consider factors that influence efficacy (weed species and their growth stages, climatic conditions) and cost-effectiveness of weed control options (mainly, herbicides), and, therefore, assist in selection of best weed-control option (Wilkerson *et al.* 2002). They may become important weed management tools and can potentially reduce prophylactic herbicide application, and herbicide loads into environment. However, these models over-simplify the complex weed-crop environment (Wilkerson *et al.* 2002), and hence, cannot simulate actual field condition perfectly, although the predictive capability can be improved with concurrent advances in computer technology. Scott

Table 2. Decision support systems/ tools for better weed management

Decision support systems/ tools	Description	Reference
HERB™	ET software application for soybean; includes many post-emergence herbicides; yield loss prediction using competitive index (CI) of weed species, higher values indicating more competitive weeds; estimates crop loss accurately at low weed densities, but overestimate at higher densities.	Wilkerson *et al.* (1991) Coble and Mortensen (1992)
NebHERB	ET software application used by Nebraska (USA) farmers; helps in post-emergence herbicide recommendations for soybean; crop loss (without weed control) is estimated using rectangular hyperbola regression equation.	Mortensen *et al.* (1993)
GWM (General weed management)	A bio-economic simulation model and decision support system (DSS) that can evaluate soil-applied and post-emergence weed management options in row crops; predicts the effect of management on weeds and crop yield in single season; parameterized to evaluate weed management as in two existing models (WEEDHA4; WEEDCAM) and for dry bean production.	Wiles *et al.* (1996)
HADSS™ (Herbicide application decision support system)	A desktop program for weed control/herbicide recommendation; information on crop, expected weed-free yield, crop sale price, estimated weed density, field history, field size, soil organic matter content, texture are required for pre-plant incorporation (PPI)/pre-emergence (PE) treatment; additional information on weed size, soil moisture content, density of each weed species are also required for post-emergence (POE) treatment.	Sturgill *et al.* (2001)
WeedSOFT™	WeedSOFT makes weed management decisions; yield loss estimated using CI of each weed species; provides fast, accurate solutions to specific weed problem; further more addresses environmental issues including ground water and surface water contamination and herbicide carry-over.	Mortensen *et al.* (1999), Krishnan *et al.* (2001)
GESTINF	Developed in Italy for making weed control decisions for soybean and winter wheat using observed weed densities, weed-free crop yield and grain price as input data; can estimate yield loss caused by weeds surviving the treatment; and consider environmental factors, thus, select treatment based on economics and environment.	Berti and Zanin (1997)
WEEDSIM	A bio-economic decision-aid model of weed management in corn and soybean; a multivariate hyperbolic yield equation; accommodates multiple weed species and multiple control measures like mechanical, chemical (PPI, PE and POE herbicides); includes estimated weed density, and predicted germination (for weed seed density estimates), weed control efficacy, yield loss, and seed production; recommends an optimal weed control strategy for a two-year time horizon and result in lower ET values than one year decision rule.	Swinton and King (1994)
SELOMA	An Italian computer program evaluates weed competitiveness and helps weed management recommendations in wheat, barley, oat, rye, sugar beet, corn, and sorghum; requires data on weed density, crop, weed growth stage and height, ET, and herbicide efficacy; recommends mechanical, chemical measures, and best herbicide.	Stigliani and Resina (1993)

et al. (2002) reported that the post-emergence herbicides recommended by HADSS™ in peanut resulted in better weed control, higher yield, and profitability than those with standard post-emergence herbicide. Hazra *et al.* (2011) used the rectangular non-linear hyperbolic regression model (weed density *vs*. crop yield; model 1; Eq. 1 and 2) and empirical model (*i.e.,* relative leaf area *vs*. crop yield; model 2; Eq. 4) in a field experiment to predict soybean yields and yield losses across the densities of *Trianthema portulacastrum* L. (horse purslane). Both the models could simulate soybean yield losses better due to horse purslane densities with R^2 = 0.85 (Model 1) and R^2 = 0.91 (Model 2). The obtained residuals/ deviations between the predicted and observed yield losses ranged from -0.3 to -1.4% in the weed density *vs*. crop yield model; and from -0.5 to -2.7% in the relative leaf area *vs*. crop yield model (Hazra *et al.* 2011). In another experiment, Hussain *et al.* (2014) determined wheat yield losses that economically justifies control of *Phalaris minor* Retz. (littleseed canary grass) by correlating per cent yield losses obtained through equation proposed by Uygur *et al.* (1999) to weed density using a linear regression model (model 7; step 1 and 2). They found that the linear regression model was effective in predicting wheat yield losses across the densities of *P. minor* and the regression equations showed good fit to observed data. The ET level of *P. minor* was estimated at 6-7 plants/m^2 for mid-sown and 2.2-3.3 plants/m^2 for late-sown wheat crop. The model predicted a yield loss to the tune of 4% at 5 plants/m^2 of *P. minor*. Similarly, using various other models, the ETs of *Chenopodium album* L. (common lambsquarters) in wheat (Dodamani and Das 2013) and of *Cyperus rotundus* L. (nutsedge) in soybean (Das *et al*. 2014b) in India; of *Bromus japonicus* (japanese brome) in wheat (Li *et al*. 2016) and of *C. rotundus* in groundnut (Du *et al*. 2019) in China were determined.

The ET values of some important weeds have been determined across the crops through several studies in the world (**Table 3**). Below the ET value, certain amount of weed interference and crop loss can be tolerated considering the unavailability of adequate human labourers, resources, and inputs required for crop production. Boz (2005) reported that control measure or herbicide application should be advocated when the economic loss caused by weeds is greater than the cost of control. Moorthy and Das (1998) reported that a density of 40 plants/ m^2 of *Cyperus iria* (umbrella sedge) with a dry matter production of 0.3 t/ha was the threshold level of this weed for adopting control measure in upland direct-seeded rice. Similarly, using empirical models, the ET of *T. portulacastrum*, the most widely distributed rainy season (*Kharif*) weed in India was found to be 6, 5 and 4 plants/m^2, considering the 70, 80, and 90% control efficiencies of the herbicide lactofen, respectively (Hazra *et al.* 2011). In India now-a-days *P. minor*. has become the most important weed in wheat, causing significant yield loss, which demands for prompt control measures. Sinha *et al*. (2009) estimated the threshold density of *P. minor* in wheat to be 25 plants/m^2 in North Bihar, India. In contrast, using a rectangular non-linear hyperbolic regression model, Raj *et al.* (2020) found that the mean ET of *P. minor* over the years was 6, 8 and 10 plants/m^2 at 100, 150 and 180 kg N/ha, respectively in New Delhi, India. The model took several production factors into consideration for estimating ET, which can make the ET of *P. minor* more precise, reliable and the *P. minor* management decision more economical. This would be useful for making *P. minor* control decision and fitting models. This also holds great potential in designing weed management strategies for other crops/cropping systems, where single weed species is dominant in crops (Raj *et al*. 2020). This may delay the likelihood of development of herbicide-resistance in weeds as well. In another study, the ET value of *C. rotundus* in soybean was estimated to be 19-22 plants/ m^2, considering a post-emergent treatment of imazethapyr with 70% efficiency (Das *et al*. 2014b). Similarly, Dodamani and Das (2013) observed that the ET of *C. album* in wheat was 6-7 plants/m^2 and the simulation of yields and yield losses using the yield-density model was better at lower weed densities up to 16 plants/m^2 than at higher densities (32, 64 and 128 plants/m^2). In Bangladesh, Mamun *et al*. (2013a) found that weed dry matter-crop yield model (Cousens 1985a) was effective in predicting yield losses over a wide range of *Scirpus maritimus* (saltmarsh bulrush) dry matter in winter rice and 10-18 g/m^2 dry matter of *S. maritimus* (or 2-4 weeds/m^2) could be allowed without economic yield loss. Similarly, the ET of different weeds have been estimated across crops in different parts of the world, such as: 1.79 plants of *Xanthium pensylvanicum* (common cocklebur) per 10 m row as ET in soybean in USA (Marra and Carlson 1983); 7.1 plants/m^2 of *Bromus sterilis* as ET in winter wheat in England (Cousens *et al*. 1988); 6 plants/m^{2}of *Ammi majus* (bishop's weed) and 4 plants/m^2 of *C. album* as ET in sunflower in Italy (Onofri and Tei 1994); 1.8-2.0 plants/m^2 of *Raphanus raphanistrum* (wild radish) as ET in wheat in Turkey (Boz 2005); 0.40-14.0 plants/ m^2 (for conventional tillage) or 0.13-3.13 plants/m^2 (for no-tillage) of *Abutilon theophrasti* (velvet leaf) as ET in maize in USA (Cardina *et al*. 1995); 5-7 plants/ m^2 of *S. maritimus* and *C. difformis* as ET in direct-

Table 3. Economic thresholds of weed species in different crops

Crop	Weed species	ET value and yield loss (%)	Country	Reference
Upland rice	*Cyperus iria* L. (umbrella sedge)	40 plants/m^2 with dry-matter accumulation of 0.3 t/ha and 11.2% yield loss	India	Moorthy and Das (1998)
Winter rice	*Scirpus maritimus* L. (saltmarsh bulrush)	2-4 plants/m^2 (or 10-18 g/ m^2)	Bangladesh	Mamun *et al*. (2013a)
Direct-seeded rice	*Scirpus maritimus* L. (saltmarsh bulrush) and *Cyperus difformis* L. (small-flowered nutsedge) (80% of total weed population)	5-7 weeds/m^2	Bangladesh	Mamun *et al*. (2013b)
Rice	*Cyperus esculentus* L. (yellow nutsedge)	2 and 13 plants/m^2 for the first (14 days) and second (21 days) period of irrigation, respectively	Brazil	Westendorff *et al*. (2014)
Rice	*Alternanthera philoxeroides* (Mart.) Griseb. (alligator weed)	1.3-1.5 plants/m^2	Pakistan	Mehmood *et al*. (2018)
Direct-seeded rice	Mixed population of weeds, particularly dominated by grass weeds	9 plants/m^2	India	Sen *et al*. (2020)
Wheat	*Bromus japonicus* Houtt. (japanese brome)	4-5 plants/m^2 at 80% efficiency of flucarbazone with 2.11-2.24% yield loss at 4 plants/ m^2	China	Li *et al*. (2016)
Wheat	*Phalaris minor* Retz. (littleseed canarygrass)	6, 8 and 10 plants/m^2 at 100, 150 and 180 kg N/ha, respectively (1.6-2.0% yield loss at 10 plants/m^2 with 180 kg N/ha)	India	Raj *et al*. (2020)
Wheat	*Lolium multiflorum* Lam. (ryegrass)	8-48 plants/m^2	Brazil	Galon *et al*. (2019)
Wheat	*Phalaris minor* Retz. (littleseed canarygrass)	6-7 and 2.2-3.3 plants/m^2 in mid- (20 November) and late-sown (10 December) wheat crop, respectively (4% yield loss at 5 plants/m^2)	Pakistan	Hussain *et al*. (2014)
Wheat	*Avena* spp. (wild oats)	39 weed seeds/m^2 or equivalent to 10.1 seedlings/m^2	Australia	Jones and Medd (2000)
Wheat	*Phalaris minor* Retz. (littleseed canarygrass)	ET ranged from 13-19.7 plants/m^2 (but, 17 and 15 plants/m^2 at 80 and 90% efficiencies of isoproturon, respectively)	India	Duary and Yaduraju (2005)
Wheat	*Raphanus raphanistrum* L. (wild radish)	1.8 to 2.0 plants/m^2	Turkey	Boz (2005)
Wheat	*Phalaris minor* Retz. (littleseed canarygrass)	25 plants/m^2 with 12.4% yield loss.	India	Sinha *et al*. (2009)
Wheat	*Chenopodium album* L. (common lambsquarters)	6–7 plants/m^2 with 3.4-4.3% yield loss.	India	Dodamani and Das (2013)
Wheat	*Avena sterilis* ssp. *ludoviciana* (Dur.) Nym. (wild oats)	1.2-2.1 plants/m^2 for isoproturon; 3.2-6.6 plants/m^2 for diclofop-methyl; 2.0-4.1 plants/m^2 for manual weeding	India	Thomas (1996) Thomas *et al*. (2000)
Winter wheat	*Avena fatua* L. (wild oats)	2-3 seedlings/m^2	England	Cousens *et al*. (1986)
Winter wheat	*Bromus sterilis* L. (barren brome)	7.1 plants m^2	England	Cousens *et al*. (1988)
Maize	*Abutilon theophrasti* Medic. (velvet leaf)	0.3 to 2.4 plants/m^2 depending upon the kill rate (from 0.6 to 1.0)	Italy	Zanin and Sattin (1988)
Maize	*Abutilon theophrasti* Medic. (velvet leaf)	0.40-14.0 plants/m^2 (conventional tillage); 0.13-3.13 plants/m^2 (no-tillage)	USA	Cardina *et al*. (1995)
Soybean	*Xanthium pensylvanicum* Wallr. (common cocklebur)	1.79 weeds per 10 row metre	USA	Marra and Carlson (1983)
	Ipomoea purpurea (L.) Roth (tall morning glory)	1.53 weeds per 10 row metre		
	Amaranthus hybridus L. (smooth pigweed)	2.92 weeds per 10 row metre		
	Ambrosia artemisiifolia L. (common ragweed)	5.19 weeds per 10 row metre		
	Polygonum pensylvanicum L. (pennsylvania smartweed)	3.00 weeds per 10 row metre		
Soybean	*Abutilon theophrasti* Medic. (velvet leaf)	0.66- 4.34 plants/m^2	Italy	Sartorato *et al*. (1996)
	Amaranthus cruentus L. (red amaranth)	0.34-1.05 plants/m^2		
	Datura stramonium L. (jimsonweed)	0.15-3.10 plants/m^2		
	Panicum miliaceum L. (wild proso millet)	0.67-4.18 plants/m^2		
	Solanum nigrum L. (black nightshade)	2.19-2.61 plants/m^2		
Soybean	*Trianthema portulacastrum* L. (horse purslane)	6, 5 and 4 plants/m^2 at 70, 80 and 90% efficiencies of lactofen, respectively	India	Hazra *et al*. (2011)
Soybean	*Cyperus rotundus* L. (purple nutsedge)	19-22 (~mean 21) plants/m^2 at 70% efficiency of imazethapyr with 9.1-11.5% yield loss	India	Das *et al*. (2014b)
Sunflower	*Ammi majus* L. (bishop's weed)	6 plants/m^2 (mechanical weed control by hoeing at 70% killing rate)	Italy	Onofri and Tei (1994)
	Chenopodium album L. (common lambsquarters)	4 plants/m^2 (mechanical weed control by hoeing at 70% killing rate)		
	Sinapis arvensis L. (wild mustard)	• 4 plants/m^2 (mechanical weed control by hoeing at 70% killing rate) • 6 plants/m^2 at 95% efficacy of imazamethabenz		
Sugarcane	*Brachiaria brizantha* (A. Rich.) Stapf. (signal grass)	0.33-0.66 *B. brizantha*/m^2 for various cultivars	Brazil	Tironi *et al*. (2016)
Peanut	*Cyperus rotundus* L. (purple nutsedge)	4-5 plants/m^2 at 90% efficiency of imazapic with 3.68-3.97% yield loss	China	Du *et al*. (2019)

seeded rice in Bangladesh (Mamun *et al.* 2013b); 1.3-1.5 plants/m^2 of *Alternanthera philoxeroides* (alligator weed) as ET in rice in Pakistan (Mehmood *et al.* 2018); 2 and 13 plants/m^2 during the first (14 days) and second (21 days) irrigation, respectively, of *C. esculentus* as ET in rice in Brazil (Westendorff *et al.* 2014); 4-5 plants/m^2 of *Bromus japonicus* as ET in wheat in China (Li *et al.* 2016); 8-48 plants/m^2 of *Lolium multiflorum* (ryegrass) as ET in wheat in Brazil (Galon *et al.* 2019); 0.33-0.66 plant/m^2 of *Brachiaria brizantha* (signal grass) in sugarcane as ET in Brazil (Tironi *et al.* 2016); and 4-5 plants/m^2 of *C. rotundus* as ET in peanut in China (Du *et al.* 2019).

Impact of weed interference on crop is a cumulative and collective effect of a large number of weeds (~composite weeds) present in crop fields except where there is abundance/dominance of single/ specific weed. Measuring the effect of single weed density, however, may not reflect total weed impact accurately (Radosevich and Holt 1984). The weed biomass per unit area could be more appropriate in determining ET values, but there is lack of models. The ET models or formulae based on composite weed density are hardly available. Moreover, it is difficult to establish a widely applicable and reproducible ET model based on composite weed density due to inherent patchy distribution, inconsistent and variable composition and population of weed species in crops across fields/locations (Das 2001) and times. Weeds also vary in their growth habits. In these situations, statistical transformation is envisaged to reduce variation in weed population for a meaningful conclusion of the treatments' effects (Das 1999). The transformed weed densities may be used for determining ET, the results of which, however, still remain uncertain. Therefore, the determination of ET is usually based on specific weed infestation in certain crops. The ET values calculated based on this method can be extended for other crop situations, having similar infestation of that weed.

Factors affecting economic threshold (ET)

Like the period threshold (*i.e.*, critical period of weed interference), the ET is a dynamic concept (Das 2008). Several factors such as weed, crops and crops varieties, nutrients (especially N), soil and climate, relative times of crop and weed emergence, herbicides cost and efficacy, cost of control and market price of produce, crop growing time (season, year) can influence crop-weed interference and thereby ET.

Weed, crop and crops cultivars

Crops and weed based on their architecture differ considerably in their ability to compete with each other (Coble and Mortensen 1992, Das and Yaduraju 1995, Das and Yaduraju 1996, Hazra *et al.* 2011, Dodamani and Das 2013, Mamun *et al.* 2013b, Hussain *et al.* 2014, Das *et al.* 2014b, Dass *et al.* 2017). Even the cultivars of a crop may have difference in their competitiveness against weed. Therefore, the ET of certain weed may vary across crops, and even between the cultivars of a crop, depending on the competitive abilities of crops or cultivars. Similarly, different weeds have different competitive abilities in a crop or across crops. Galon *et al.* (2016) determined the ET of *Bidens pilosa* L. (beggartick) in six black bean cultivars, ranging from 0.59-8.72 plants/m^2. The difference in ET was attributed to the intrinsic growth habit of each cultivar, reflecting plant stature, leaf size, branching capacity, which could influence light entry into soil, thus, weed infestation, and yields of cultivars (Mason *et al.* 2007). Furthermore, tolerance of crops against weed pressure is associated with its ability to acquire resources including water, nutrients and light, and allelopathic effects on weeds. Usually, competitive cultivars have vigorous growth that can suppress weeds efficiently through reducing the supply of resources to weeds (Buhler 2002, Dass *et al.* 2017). These effects minimize weed interference and subsequent crop yield loss, thereby significantly influencing the ET of a weed.

Climate, soil and cropping season

Composition and distribution of weed species are influenced by the changes in physical and biotic pressures of the environments (mainly, climate and soil) in which they grow. This influences ET and makes it dynamic is influenced by them. An alteration (permanent or temporary) in any of the environmental factors, biotic or abiotic, or introduction of new factors may considerably alter the abundance, composition and distribution of weed species in given area (Stern *et al.* 1959). Optimal climatic and edaphic factors, such as temperature, soil moisture and fertility can have more significant effects on optimal crop plant density relative to weeds (Walker and Buchanan 1982) and influence ET of weed considerably. Moreover, soils with relatively higher amounts of organic matter and clay content show carry-over effects of control measures, mainly herbicides from the preceding crops that may result in lowering ET values. The time of weed control operations, for example, application of herbicides is crucial for effective weed control that may significantly influence ET. The warm and humid conditions during rainy season favours weeds more relative to crops, and weeds grow more rapidly and vigorously during rainy season than winter. This can influence weed interference and ET. Similarly, weather/climatic variations that have direct effect on crop and weed growth over the years can also influence ET. The best time of weed control, *i.e.*, the length of critical period of crop-weed competition also depends on other conditions such as time of weed emergence, density and competitive ability of weeds and environmental factors. Controlling weeds during the critical period helps in minimizing higher crop-weed interference and avoids significant yield loss (Das 2008, Nazarko *et al.* 2005). Weed control operations outside this period (too early or too late) may have little effect on weed management or crop yield. Moreover, herbicide applications at the appropriate time may help farmers save one spray operation thereby reducing the cost of weed control and ET.

Nutrients

Crop-weed interference *vis-à-vis* ETs are considerably influenced by the availability of nutrients, especially N, depending on weed species and their composition and distribution (Das and Yaduraju 1999, Blackshaw *et al.* 2004, Das and Yaduraju 2007, Das and Yaduraju 2011). Certain weed growth and consequent yield losses due to interference could be reduced by applying higher doses of N (Das and Yaduraju 1999, 2007, 2011). Raj *et al.* (2020) reported that the higher N doses, 150 and 180 kg N/ha could lead to 25% and 43% reduction in *P. minor* density, respectively compared to 100 kg N/ha. Moreover, the yield reduction at a higher density of 80 *P. minor* plants/m^2 was substantially lower due to 180 kg N/ha (~1.1 t/ha) compared to 100 and 150 kg N/ha (*i.e.*, 1.7 and 1.3 t/ha, respectively). In a similar study, it was observed that the growth of *C. album* and wheat increased gradually with the increase in N level from 0 to 120 kg N/ha, but the application of 120 kg N/ha favoured wheat growth more than that of weed, resulting in greater crop-weed balance compared to sub-optimal dose of 60 N kg/ha (Dodamani and Das 2013). Thus, the nutrients, particularly N could be a management option for weeds in wheat, resulting in higher ET values (Das and Yaduraju 1999; Raj *et al.* 2020).

Crop yield and price, herbicide efficacy and cost of control

The ET values of a weed could be different in the same crop at various yield levels due to differential weed interference. Hussain *et al.* (2014) reported a lower ET of *P. minor* (~2.2 - 3.3 plants/m^2) in late-sown wheat compared to 6-7 plants/m^2 in timely-sown crop, primarily owing to high weed pressure and lower grain yield. Similarly, higher growth of *C. album* and consequently lower wheat yield could reduce ET slightly compared to normal (Dodamani and Das 2013). Efficiency of herbicides is another profound factor influencing ET. Generally, higher the herbicide efficiency, lower is the ET (Hazra *et al.* 2011).Galon *et al.* (2019) made a comparison between the ETs across herbicide efficiencies and found that the ETs of ryegrass were 12.5% higher and 9.8% lower at 80% and 100% herbicide efficiencies, respectively compared to that at 90% herbicide efficiency. The ET of weeds is usually lower in crops with higher market price, and even a small yield loss could be an economic loss under this situation (Hazra *et al.* 2011, Dodamani and Das 2013, Li *et al.* 2016, Du *et al.* 2019). There is implication that an increase in cost of weed control will lead to increase ET, indicating greater number of weeds/m^2 to justify adoption of control measures. Hand weeding may have higher ET value than herbicidal treatment due to higher wage. Furthermore, any increase in crop yield and price, degree of weed control, or crop loss per unit weed density will lower ET, other factors being constant (Coble and Mortensen 1992). Thus, the variations in crop and weed growth/vigour, cost of weed control, price of produce, and herbicide efficiency across locations and time (Fischer *et al.* 2004, Duary and Yaduraju 2005, Cheema and Akhtar 2006, Hazra *et al.* 2011, Dodamani and Das 2013) are responsible for variations in ET.

Usefulness and limitation of ET

In weed science, the ET concept has been advocated as a decision-making tool to farmers for determining whether or not to adopt weed control (i.e., when weed populations exceed a certain level). The ET provides a base for rational use of weed control measures/operations by excluding unnecessary control operations (especially herbicide use), thereby increasing the effectiveness of weed management. Thus, ET-based weed management strategy may lead to the rationalization and reduction of herbicide use (both amount and cost) and environmental damage (*i.e.*, pesticides loads) while maintaining farm productivity and profitability as well as sustainability of chemical weed management. Despite of numerous potential benefits, the adoption of ET for weed control has been low among the growers. The concept of ET has been criticized for a number of reasons: (i) Proven *et al.* (1991) opined that the methods for ET determination are generally too laborious to be adopted by farmers. Factors like herbicide and its application cost, unit crop value involved in estimating ET, can be estimated accurately, but the potential crop yield (weed-free yield), per cent yield loss, weed density and herbicide efficacy are comparatively more difficult to determine owing to spatial heterogeneity (inherent patchiness) of weed population and variability associated with weed composition, weather, and cropping systems effects on these variables (Auld and Tisdell 1987, Auld *et al.* 1987, Mortensen and Coble 1989, Proven *et al.* 1991, Coble and Mortensen 1992). These make accurate estimation of ET difficult; (ii) assessment of yield losses due to weeds is based on simple weed densities but several factors influence yield losses including weather conditions, relative time of crop and weed emergence, crop stand and potential yield, crop value and cost of weed control. The crop-weed interactions depend greatly on weather conditions that even may differ for the same crop-weed pair (O'Donovan 1996, Hall *et al.* 2000, O'Donovan and McClay 2002).The ET however largely ignores these factors and over-simplifies the estimation; (iii) weed control decision-making through ET is largely a single-season approach. It simply overlooks the carry-over effects of residual weeds at sub-threshold densities. These 'escapes' may return large amounts of weed seed (weed seed rain) to the seed bank, creating seed bank build-up in soil and potential future weed problems (Cousens 1987, Buhler *et al*. 1997, Norris 1999). This may increase the cumulative herbicide use over the years (10-15 years) for controlling weeds resulting from sub-threshold residual weeds (Pandey and Medd 1990). The ET also does not consider the carryover effects of residual herbicides in soil. This interrupts the decision-making in future years. Economic optimum threshold (EOT) has been suggested as an improved and preferred tool over the ET as this takes into consideration the future weed population dynamics and seed production (Cousens 1987). Several studies have found that the EOT of weed was considerably lower than that of ET when future population dynamics/ effects were taken into account (Cousens *et al*. 1986, Doyle *et al*. 1986, Bauer and Mortensen 1992, Swinton and King 1994). In a study, weed population dynamics was incorporated into a dynamic, multiple species, multiple control 2-year bio-economic model (WEEDSIM) that resulted in a significantly lower ET for 3-weed species than one year decision rule (Swinton and King 1994). The EOTs of two weed species were 7.5-fold and 3.6-fold lower than their respective ET in a continuous soybean system (Bauer and Mortensen 1992). Therefore, seed production by uncontrolled weeds would result in lowered population threshold over a period of years than those computed on weed interference alone. Thus, the use of EOT (with very low values) may not result in a significant reduction in herbicide use and consequent economic gain (Jones and Medd 2000, Nazarko *et al.* 2005); (iv) most ETs have been estimated based on single crop-weed interaction. Research on ET with multiple weed species is limited especially in cropping systems containing diverse weed species with different competitive abilities (Hall *et al*. 2000, Nazarko *et al*. 2005). Moreover, most of the research assumed the impact of multiple weed species on crop yield to be additive, which is not always true (Swanton *et al.* 1999); (v) The ET concept considers a fixed dose of single herbicide as the only weed control option with little information on variable herbicide rates depending upon weed density and environmental conditions. It precludes the opportunity of incorporating other chemical and non-chemical options for integrated weed management (Jones and Medd 2000). Optimal dose rate (ODR) has been proposed as an improved framework of variable herbicide rates over the existing fixed rate (Deen *et al*. 1993, Pannell 1995). However, ODR still ignores the residual weed densities and carry-over effects of herbicides (Jones and Medd, 2000); (vi) the ET advocates leave some weeds below the threshold levels in the field. But, high level of weed control and a weed-free crop (for ease of harvest and grain quality) are the primary desires of a farmer that might not happen by using ET concept; (vii) applicability of ET concept is to be restricted while dealing with the management of herbicide-resistant weeds. Seeds produced from the sub-ET density of herbicide-resistant weeds may cause severe weed menace in future and failure of existing weed management practices. The ETs are mainly suitable under low weed pressure situation. Therefore, combinations of practices that reduce weed densities or competitiveness are particularly important for realizing the potential of reducing herbicide use through ET (Nazarko *et al.* 2005).

Long-term approach for economic threshold

Weed control using ET is largely a single-season and short-term approach, which may lead to build up seed bank in soil over the years (discussed above). A model based on long-term weed populations considering the weed seed bank may be used as an alternative to the single-season approach of weed control decisions making (Jones and Medd 2000). Depletion of weed seed bank in soil over the years should be the primary aim of this approach while maximizing the long-term farm profitability. However, this approach needs a comprehensive understanding of weed population dynamics and the use of integrated weed management strategies. This approach was applied to a model for controlling wild oat in spring wheat and as a result of this wild oat seed bank in soil reduced to almost zero owing to low tolerance for weeds in the first few years (Jones and Medd 2000). The adoption of integrated weed management practices took only seven years to deplete the weed seed bank while it took nearly 15 years for the same when only chemical weed control was used (Jones and Medd 2000). Herbicide use was higher during the initial years to deplete seed bank, yet the total herbicide consumption of 20 years was much lower compared to controlling weeds according to ET (Jones and Medd 2000). Thus, lower tolerance for weeds during the initial years is important for depleting weed seed bank more quickly and lowering herbicide use and delaying resistance development in weeds against herbicide.

Conclusions

The ET can be a major decision-making framework for effective and profitable weed management while ensuring rationalization of herbicides use and environmental security. The ET-based decision holds great potential in designing weed management framework for a single-season cropped situation and in crops where single weed species dominates. Prediction of yield loss due to single weed species may not reflect weed impacts adequately in the long-run, especially in cropping systems having multiple diverse weed species. Moreover, this approach does not consider the long-term effect of residual weeds on seed bank. Therefore, adoption of ET by farmers has been low, despite the availability of several models. More information on crop-weed interactions using current crop production systems and cultivars, weed emergence patterns, and the spatial heterogeneity of weeds is needed to improve the determination of economic or action thresholds. An alternative could be using a model based on long-term weed populations that aims to deplete weed seed bank while optimizing farm profitability. While developing these models, more comprehensive information including weed population dynamics in cropping pattern, biology of weed species such as weed reproduction and seed dormancy, vegetative allocation patterns of both weeds and crops, integrated weed management strategies, *etc* must be considered. This would lead to making an economical, reliable and precise weed control decision that may reduce future weed problems and environmental footprints of herbicides.

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