Ecological Implications of Using Thresholds for Weed Management

Robert F. Norris

SUMMARY. Various types of thresholds have been developed for weed management in an attempt to provide a more rational approach to decision making. The economic threshold concept was originally developed for management of arthropod pests, and is based on an understanding of arthropod population biology. Adoption of a management strategy for weeds that was developed for maintaining arthropod populations below a damaging level, referred to as the economic injury level or EIL, is not ecologically sound. Many of the factors that regulate populations of the two types of pest are different. For arthropod management the economic threshold (ET) is defined as the pest population at which treatment should be initiated to stop the population from increasing to the EIL. Weed science has adopted the ET to be the same as the EIL; this leads to maintenance of a relatively high seed bank as weeds at or below the ET density are allowed to produce seed. Research where weed seed production was accurately determined in corn, sugarbeets, alfalfa and other crops is now suggesting that several important weed species should be managed so that they do not produce seed. I am proposing that a new threshold called a no seed threshold, or NST, should be established for such weeds. Application of the ET concept to an invading weed species is disastrous as it leads to establishment of the seedbank before any control action is taken; for an invading species that is expanding its range the use of NST seems more appropriate. Progressive farmers in California have adopted NST for management of weeds. These farmers claim that the strategy is economically superior to that

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using single season ET. In one case adoption of NST for weed management has resulted in decreased reliance on herbicides as weed control can be attained using non-chemical techniques. There is urgent need for weed science to develop improved data on weed population dynamics that is coupled to economics of weed control and crop production; until such data become available it is not feasible to accurately assess the use of thresholds for weed management. *[Article copies available for a fee from The Haworth Document Delivery Service: 1-800-342-9678. E-mail address: getinfo@haworthpressinc.com]*

KEYWORDS. Economic thresholds, invasion, no seed thresholds, pest management, population dynamics

WEEDS AND THE THRESHOLD CONCEPT

The concept of utilizing economic thresholds to provide a more rational way of making pest control decisions originated in the 1950s (Stern et al., 1959). The first efforts were all directed towards more rational management of arthropod pests, and the concept of economic thresholds is now well established for integrated pest management (IPM) programs for many arthropod pests (see Stern, 1973; Pedigo, Hutchins and Higley, 1986; Pedigo, 1996). In its simplest form the concept attempts to relate the population development of an arthropod pest (Figure 1) to the anticipated single season crop loss from such pest attack (Figure 2). Economic thresholds have also been developed as a component of the decision making for nematodes (Ferris, 1978; Osteen, Moffitt and Johnson, 1988), and pathogens (Zadoks, 1985). This paper addresses utilization and applicability of thresholds for weed management, proposes a new threshold, reviews published data supporting the concept of not letting weeds set seed, briefly explores the problem of using thresholds to manage invading weed species, and concludes with two examples of farming operations that use stopping weeds from producing seed as a management philosophy.

In response to mounting pressure to reduce herbicide use, and as a component of IPM programs in crop production, there has been considerable effort made to develop economic thresholds for weed management (Coble and Mortensen, 1992). There are now several examples of economic thresholds being developed for use in cereal production (Cousens et al., 1986; Heitefuss, Gerowitt and Wahmoff, 1987; Gerowitt and Heitefuss, 1990; Black and Dyson, 1993; Zanin, Berti and Toniolo, 1993; Kwon et al., 1995). There has also been considerable effort to develop economic thresholds for decision making for weed management in soybeans [*Glycine max* (L.) Merr.] (Coble, 1985;

FIGURE 1. Hypothetical example of pest arthropod populations dynamics in relation to time, showing relative position of economic threshold and economic injury levels. GEP is the general population position at which the population stabilizes between outbreaks. Dashed line = population without control, solid line = population with control.

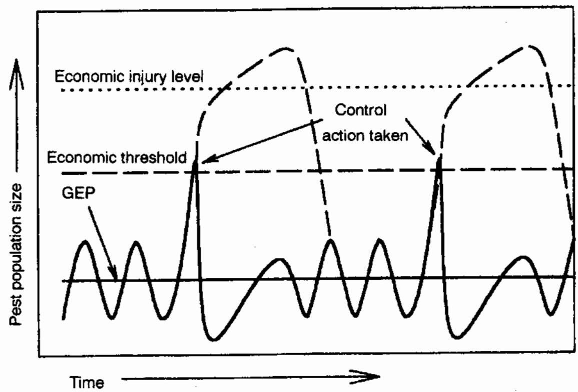
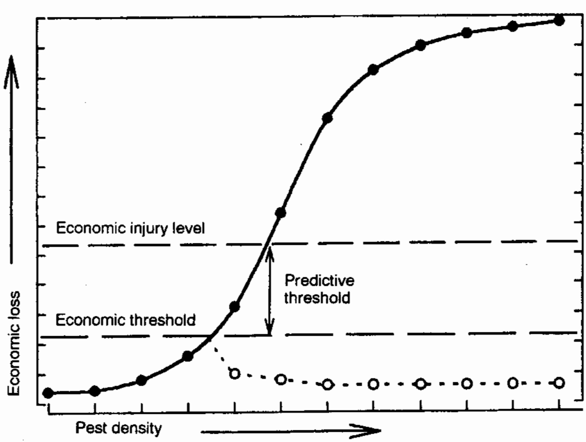


FIGURE 2. Generalized relationship between pest density and economic loss. Dotted line with open circles represents the population following a control action applied when the economic threshold had been exceeded.



Renner and Black, 1991; Weersink, Deen and Weaver, 1991; Wilkerson, Modena and Coble, 1991; Bauer and Mortensen, 1992) and corn (*Zea mays* L.) (Lybecker, Schweizer and King, 1991; Sattin, Zanin and Berti, 1992; Cardina, Regnier and Sparrow, 1995; Berti et al., 1996; Bosnic and Swanton, 1997). Examples of other crops in which researchers have attempted to establish single-season economic thresholds include alfalfa (*Medicago sativa* L.) (Légère and Deschenes, 1989), onions (*Allium cèpa* L.) (Dunan et al., 1995), sugarbeets (*Beta vulgaris* L.) (Norris, 1992a) and tomatoes (*Lycopersicon esculentum* L.) (Akey et al., 1995a). The general principles of applying thresholds for weed management have been extensively discussed (e.g., Cousens, Wilson and Cussans, 1985; Cussans, Cousens and Wilson, 1986; Auld, Menz and Tisdell, 1987; Cousens, 1987; Thornton et al., 1990; Doyle, 1991; Jordan, 1992; O'Donovan, 1996; Wallinga and van Oijen, 1997) and the reader is referred to these papers.

There are several fundamental problems with the way that the economic threshold concept has been applied to weed management. Weed science seems to have equated the economic threshold with the economic injury level; this creates a fundamental problem in relation to timing of initiation of control measures. The second problem is that the economic threshold concept as applied to weed management exacerbates development of herbicide resistant weeds. If we continue to use economic thresholds, as currently defined for weed management, I feel that we can assure ourselves of an ever increasing problem with herbicide resistant weeds. The use of economic thresholds for managing invasive weeds is another fundamental strategic error, as the approach allows the plant to become established before any control action is initiated. Utilizing economic thresholds requires high levels of weed management in each crop, and I argue that the whole concept is thus dependent on availability of herbicides to control the inevitable weed population that *will be* present in the field each year. Without herbicides it is doubtful if the economic threshold concept could be utilized. The modeling approach used by Wallinga and van Oijen (1997) suggests that the economic underpinning of the economic threshold concept is, in fact, flawed in relation to long-term weed management.

There are compelling biological and ecological reasons why the adoption of single season economic thresholds for weed management should be questioned. This paper expands and updates ideas presented at the First International Weed Control Congress in Melbourne (Norris, 1992b). I argue that the economic threshold paradigm as utilized for arthropod management does not lead to sound long-term economic weed management. This paper will present arguments based on the biology and ecology of weeds to support this position; others have presented mathematical arguments supporting the same position (Wallinga and van Oijen, 1997). At the outset I realize that some of the positions I am taking in this paper will be controversial; if I stimulate discussion and thinking about the utilization of thresholds in weed management, then I feel that my efforts will have been useful.

DEFINITIONS

In reviewing literature on economic thresholds it is apparent that different authors define thresholds in different ways. Cousens (1987) reviewed various types of thresholds that have been used, and interpreted them in relation to weed management. I have used these definitions and incorporated ideas presented by Weersink et al. (1991), Coble and Mortensen (1992) and Donovan (1996). I have also included information from entomological definitions (Stern et al., 1959; Stern, 1973; Pedigo, Hutchins and Higley, 1986; Pedigo, 1996).

Threshold: This unqualified term is often used, but is of very little value because it is too vague. It simply means the lowest level of stimulus to which there is a reaction. Its use should be avoided in relation to weed management.

Competition threshold: This implies that as weed density decreases there is a level below which there is no further loss. Biologically this does not make sense, and Cousens (1987) argued, and I concur, that the term should not be used.

Statistical threshold: This is referred to as a damage threshold in most of the entomological literature. It is the point at which statistically valid yield (or other parameter) losses can be determined. It has been given various other names by weed scientists (see Cousens, 1987).

Economic injury level (EIL): This threshold is usually not discussed in relation to weed management, and was not included by Cousens (1987) or by Coble and Mortensen (1992). It is defined as "the lowest population density which can cause economic damage." It is sometimes also referred to as the "damage threshold" (Figure 2). As far as I can determine this is the threshold that most weed scientists call an economic threshold (see below). Weersink, Deen, and Weaver (1991) note this discrepancy in their discussion of economic thresholds for weed management. Lack of application of the EIL concept is a fundamental problem in the way that thresholds are being used for weed management.

Economic threshold (ET): This is typically defined by weed science as the point at which losses equal cost of control (Cousens, Wilson and Cussans, 1985; Auld and Tisdell., 1987; Cousens, 1987; O'Donovan, 1996). There is, however, a fundamental difference between how this threshold is used by weed scientists and by entomologists. The definition presented by Cousens (1987) states that the ET is "that weed density at which the cost of control measures equals the increased return in yield which could result" and is widely accepted by weed science. The entomological definition of ET states that it is "that pest density at which control measures should be initiated to prevent an increasing pest population from reaching the EIL" (Figure 2). When ET is equated with EIL the population is treated much later in its development and economic loss will have occurred. This is exactly the situation in which weed science finds itself when adopting the ET definition given above. This will be discussed at greater length below.

The definition given above implies a single cropping cycle. Throughout this paper the use of the term economic threshold implies the single-season nature of the definitions used above.

Predictive threshold: This is the difference between the ET and the EIL (Figure 2). For insects and pathogens the ET is always lower than the EIL. The predictive threshold thus implies that management action must be taken *before* attaining the EIL. For weeds this question has not been addressed due to the equating of EIL and ET, but attempts to develop EOT (see below) suggest that the ET is perhaps 2- to 10-fold lower than the EIL. Another way to state this is to say that for a weed population, the ET occurs one to several *years* prior to achieving the EIL.

Economic optimum threshold (EOT): This threshold was proposed by Cousens (1987) and is now seeing limited use in weed science. The EOT attempts to include the economic impacts of the multiyear population dynamics characteristic of weeds (Jordan, 1992). It is not used in the other pest management disciplines. Modeling suggests that the EOT is lower than the (single season) ET (Table 1). There are, however, no actual examples of weed population dynamics data for different threshold management levels to support these model predictions.

If weed science were to adopt the use of EIL and ET as defined by entomologists there would be no need for EOT. The use of ET to prevent a population from achieving an EIL would automatically mean that the long-term nature of weed population dynamics would be considered. This would require that weed science reevaluate how it is currently using the term ET.

Safety threshold: This threshold attempts to allow a safety margin due to uncertainty about economics and the actual losses that will occur. The result is lower values than for ET, but reduction is not well defined.

Visual threshold: This is an intuitive threshold, and is basically what is visually acceptable to the land manager. It is probably the threshold that many farmers and pest control advisors use (see Czapar, Curry and Wax, 1997). It is difficult to quantify.

Action threshold: This threshold is defined as the population at which a grower decides to institute a control tactic (Coble and Mortensen, 1992). This is a combination of economic threshold, safety threshold and visual threshold.

No seed threshold (NST): This threshold is defined on the basis that weeds present or remaining in a field should not be permitted to set seed (Norris,

TABLE 1. Comparison of predicted economic threshold (ET) and economic optimum thresholds (EOT) for weeds in several crops.

Weed	Crop system	ET	EOT	Reference
Wild oat	Cereals	8 to 10/m^2	2 to 3/m^2	Cousens et al., 1986
Blackgrass	Cereals	around 30/m^2	7.5/m^2	Doyle, Cousens, and Moss, 1986
Velvetleaf	Soybeans	2.1/m^2	0.3 to 0.4/m^2	Bauer and Mortensen, 1992
Sunflower	Soybeans	1.2/m^2	0.4/m^2	Bauer and Mortensen, 1992
Velvetleaf	Corn	Probably zero	–	Cardina, Regnier and Sparrow, 1995
				Cardina and Norquay, 1997
		Zero	–	Zanin and Sattin, 1988; Sattin, Zanin, and Berti, 1992
Hempnettle	Alfalfa and oats	Zero	–	Légère and Deschenes, 1989
Barnyardgrass	Tomatoes	Zero	–	Akey et al., 1995a
Barnyardgrass	Sugarbeets	Zero	–	Norris, 1992a

1995). Weeds that will not be producing seed by harvest (e.g., emerged too late) and which do not reduce crop yield (or cause other problems, such as harvest difficulty) would be permitted to grow. It is feasible that this threshold may not be applicable to broadcast low-value crops but rather be applied to relatively high value row crops. This concept will be developed further in this paper.

Zero threshold: This implies that weeds are not allowed to grow. It is widely discussed as a management option, but was not included by Cousens (1987). This concept invokes a negative connotation due to the absence of plants other than the crop.

ARTHROPOD AND WEED POPULATION ECOLOGY

The threshold concept is based on understanding pest population biology. Stern et al. (1959) and virtually all publications since then place the different thresholds (EIL, ET, etc.) for arthropod populations in relation to population development (Figures 1 and 2). Although many of the current threshold concepts were initially developed for arthropod management, they have been adopted for weed management with little change. There are, however, fundamental differences in the ecology and population biology of weeds and arthropods that lead to different interpretations of how these principles can be applied to using threshold management concepts for the two classes of pests (Table 2). The following discussion expands the comparison between the two types of pest organism.

Trophic level: Weeds are producers in an ecosystem trophic dynamics sense. They are green plants that carry out photosynthesis and can manufacture sugars from carbon dioxide and water using energy from sunlight. Arthropods are consumers, and therefore must ingest complex organic molecules as food. Pest arthropods that feed on crop plants, for which most thresholds have been developed, are thus primary consumers, or herbivores, feeding on the producers. In many instances weeds can actually serve as a food source for plant pest arthropods.

Resource supply and the factors regulating the population of the consumer are not the same as those for the producer. The resources for weeds are water, light, carbon dioxide and mineral nutrients. Weed population dynamics can be directly altered by changes in these resources. Light availability under a canopy, for instance, can substantially alter weed population dynamics (seed output). The resources for arthropods are the plants or other consumer organisms. Any effect of primary ecosystem resources on arthropods is indirect; changing light intensity has almost no direct effect on arthropod population dynamics. If the concepts of bottom-up and top-down driven trophic dynamics are used then the plants (weeds?) drive the system in the former, and in the

TABLE 2. Aspects of the population ecology of weeds and arthropods compared.

Population parameter	Weeds	Arthropods	Implications for thresholds
Trophic level	Producers	Consumers	Use different resources
Longevity	Persistent seedbank	No long-term carryover for most spp.	Long-term implications
Population decrease	Populations decline slowly; do not "crash"	Populations usually "crash" at some time of the year	Population controls and loss rates differ
Generation time	1 or less generations/yr	1 to multiple generations/yr	Time scales differ
Population synchronicity	Population not synchronous	Population often synchronous	Prediction reliability
Population initiation	Delayed emergence	Repeated generations	Prediction difficulty
Organism mobility	Most are stationary (but moved by human activity)	Mobile	Prediction differences; invasion processes different
Off-season survival	Dormancy; survive within the managed ecosystem	Hibernation/aestivation; often not within managed ecosystem	Prediction difficulty
Fecundity per individual per generation	Relatively high fecundity: typically 1:1000 to 1:1000000+ per generation cycle	Relatively low fecundity: 1:100 to 1:1000+ typical per generation cycle	Rapidity of population regeneration
Damage potential	'Damage'/individual varies	Damage/individual ± fixed	Prediction of damage/loss

latter the herbivores drive the system. Whichever system is functioning it is not reasonable to expect that the economic thresholds for the consumer will operate in a manner similar to those for the producer.

Longevity: The longevity of the population affects population size, genetic turn-over, and size of initial population at the start of the season. Weeds typically produce seeds which, in turn, will produce the next generation. Weed seeds can remain viable in the soil for many years. A short-lived weed might have seed that remains viable for 2 to 5 years, while many long-lived weed seeds can persist for in excess of 20 years, and reports of over 100 years have been made for several species. This leads to considerable overlap of generations, with a phenomenon in the seed bank that has been referred to as "genetic memory." For most pest arthropods there is no equivalent to the seedbank, and typical longevity of any one generation is from a few days to about one year. There are some noted exceptions, such as cicadas and shrimps. There is little population overlap between generations except within a season, and thus there is no "genetic memory" in the sense that there is for a weed seedbank containing seeds produced in several different years. The ability of weeds to establish a seedbank dictates that the management paradigm for weeds should be different from that used for arthropods.

Population decrease: Weed populations decline slowly over time due to long-lived seeds with varying levels of dormancy (see below). Unless catastrophic events (e.g., flooding, fire) kill plants, the seedbank decline typically follows an exponential decay. Arthropod populations often "crash"; they experience a sudden large decrease in numbers due to natural events like an epizootic, hot or cold weather, and seasonal changes. Only those members of the population that are in the suitable stage to survive the crash will survive to the next favorable season. This means that an arthropod population can decrease from damaging (above EIL) to inconsequential (below ET), within a day or two to a few weeks. This type of population decrease *does not occur* for weeds, for which population decrease occurs over a few to many years (Wilson and Lawson, 1992; Thompson, Band and Hodgson, 1993; Burnside et al., 1996; Radosevich, Holt and Ghersa, 1997). The threshold concept works well for a population of multivoltine consumer organisms that crashes each year, but is not readily applicable to univoltine consumer pests (Pedigo, Hutchins and Higley, 1986; Pedigo, 1996). This difference between utility of economic thresholds for univoltine and multivoltine arthropods raises a question about applicability of economic thresholds for producer organisms for which the population continues from year to year.

Generation time: The typical generation time for most weeds is one year; some perennial species may, however, require several years before any offspring are produced. The generation time for univoltine arthropods is once per year. In contrast, multivoltine arthropods have generation times that range from a month or two to as short as a few weeks. Most arthropod thresholds are for those species that possess multivoltine population dynamics; this means that the population can increase rapidly *within* the season. Examples include aphids, mites, Lygus bugs, *Helicoverpa zea* Bodie (bollworms, corn earworms, tomato fruitworm), numerous other Lepidopteran pests, leafminers (*Liriomyza* spp.), whiteflies (*Bemisia* spp.), etc. Controlling one of these types of arthropod pest at the ET delays or stops the population from attaining the EIL. The use of thresholds is considered much less feasible for univoltine arthropods (Pedigo, Hutchins and Higley, 1986; Pedigo, 1996). On the basis of generation time weed population dynamics are not suitable for use of economic thresholds as employed for management of multivoltine arthropods.

Population synchronicity: Populations of weeds are not synchronous. Due to population overlap for perennials, and varying levels of seed dormancy in annuals, a weed population is typically made of individuals of differing chronological ages. The difference in age of individuals in the population range from a few weeks to several years. This can create difficulty in obtaining effective control even if decision making is not affected. Populations of many arthropod populations are synchronous. All individuals hatch within a few days, the adults mate and lays eggs within a few days, and the adults often die within a few days of each other. Population synchronicity improves the ability to make economic threshold decisions for many arthropod pests as it improves the reliability of predicting events and damage. Lack of population synchronicity in weeds makes economic threshold decisions much less reliable, and decreases the chances that a control strategy will be successful.

Organism mobility: Populations of most important weeds are not mobile (unless aided by animals or humans). Weed populations are typically fairly stable in a particular field (specific agroecosystem), and thus their size can be predicted over time. Many pest arthropods are mobile, at least in one phase of their life-cycle (usually adults). Also, many pest arthropods are not present in the managed ecosystem during the off-season. This means that they must migrate back to the field in, or must build-up to, damaging numbers. In either case using an economic threshold can suggest treatment before the EIL is attained. For most weeds the population is already present in the field at the start of the season even if it is not readily visible. On the basis of organism mobility using an economic threshold concept for weed management that was originally developed for management of mobile arthropods does not make sense. The case of weeds with wind-borne seeds [such as groundsel (*Senecio vulgaris* L.), prickly lettuce (*Lactuca serriola* L.), willowherbs (*Epilobium* spp.)] is special as they can invade previously non-infested fields without human or animal intervention, and is further discussed under the topic of thresholds in relation to invasion of weeds.

Off-season survival: Most weed seeds possess from one to several mechanisms of dormancy that regulate the percentage of the population that will germinate at any particular germination event (Radosevich, Holt and Ghersa, 1997). Arthropod populations can also exhibit dormancy, and either hibernate or aestivate to minimize the impacts of the non-favorable season (Pedigo, 1996). Arthropod dormancy typically lasts for only one off-season, whereas weed dormancy can last for many years. These two different survival strategies result in different ways in which populations are regulated.

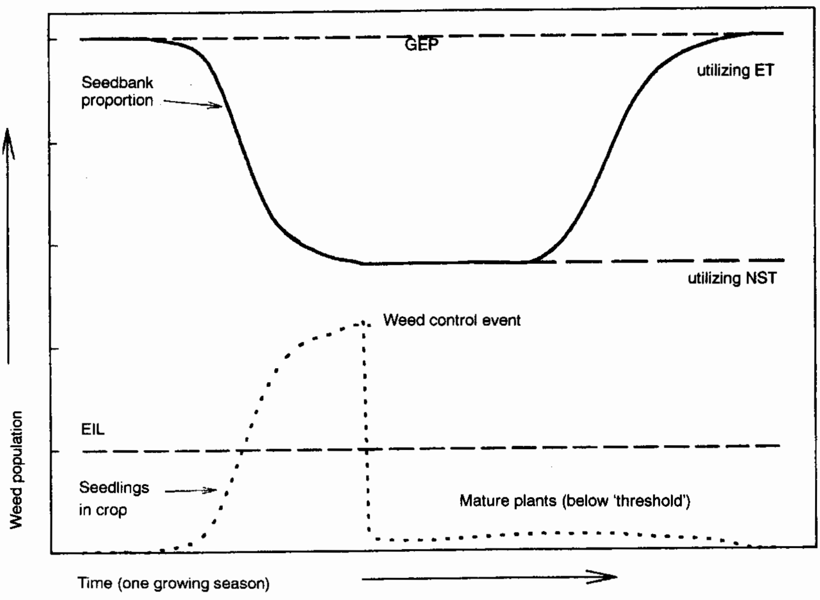
Fecundity per generation: Many weeds produce more than 1000 seeds/plant when permitted to grow in crops that are weak competitors, and recent evidence is showing that several common weeds can produce over 100,000 seeds/plant when growing in less competitive crops. Most arthropods produce from 10s to 100s of offspring, but few exceed 1000 per individual. In conjunction with the multivoltine nature of many arthropod populations the fecundity per individual leads to different rates of population increase between weeds and arthropods. Many common weed populations can explode *in a single generation* (and do not crash). Most arthropods require three or four generations to build up to similar population levels. If a fecundity of 100 offspring per individual is assumed, and there is no population regulation between generations (extremely unlikely) it will take between three and four generations to achieve the same population that a single parent producing 100,000 offspring per generation achieves. This difference in population increase between weed and arthropod populations leads to a different interpretation of economic threshold time-frame. In the case of many arthropods the time-frame is less than a growing season; for most weeds the time-frame is many years.

Damage potential: The amount of yield loss per individual weed plant is variable over a wide range depending on conditions such as time of year at emergence (day length), soil fertility, proximity and type of neighbors, and soil moisture. A mature redroot pigweed (*Amaranthus retroflexus* L.) plant that is 10 cm tall does not cause the same competitive loss as one that is 150 cm tall, yet this range of size can commonly occur in a single field. In contrast, an arthropod of equivalent developmental stage of a single species can be expected to cause essentially the same amount of damage as another individual of the same species and developmental stage. A numerical estimate of the pest arthropod thus provides a fairly reliable estimate of the amount of damage that will be sustained. A numerical count of weeds present may, however, have little relationship with the amount of damage that will be sustained. This necessitates questioning the meaning of economic thresholds for weeds that are based on numerical counts of individuals present.

These differences in biology/ecology lead to very different population dynamics between a multivoltine arthropod and an annual weed. A typical population development of an arthropod population is shown in Figure 1. The population at the beginning of the season is relatively low and said to be at the general equilibrium position or population (GEP). When conditions are correct the population increases; if it exceeds the economic threshold control action is taken to keep the population from increasing to a damaging level.

The population dynamics of any weed that reproduces by seed is different (Figure 3). Due to the presence of the seedbank, the GEP is initially high. A portion of the population germinates under favorable conditions, and becomes seedlings. At this point there is little decline in the overall population, but the size of the seedbank has decreased proportionally to the number of seeds that germinated. Following a control action the total population is

FIGURE 3. Theoretical population dynamics of an annual weed with seedbank showing the proportions of the population represented by the seedbank and the growing plants. Abbreviations: GEP = general equilibrium position; EIL = economic injury level; ET = economic threshold; NST = no seed threshold.



reduced in proportion to the number of germinated seeds that were killed, and the above ground population is reduced to whatever is the accepted "threshold." For an economic threshold, as defined earlier for weed science, seed production by the weeds judged below the threshold has the potential to return the seedbank to its original size when the system is operating with equilibrium populations. Utilization of NST would result in a seedbank that is lower than the original value by the amount of germination, plus any predation and death that occurred. Continued annual use of single season economic thresholds for weeds results in a relatively high GEP, with a more or less stable seedbank. The use of NST is predicted to result in a stepwise decline in the seedbank each time there is a germination event. The use of EOT would result in a seedbank that is lower than that maintained if ET is used, but will still be adequate to assure a rapid increase in weed population if control strategies were relaxed. Use of NST raises a question regarding the difference in cost between implementing EOT vs. NST. I argue that the slight increase in cost in going from EOT to NST is more than offset by the reduction in weed population in future years. Resolution of this question awaits results of long-term management experiments.

The foregoing discussions show that there is a fundamental difference in management strategy used against arthropod pests and against weeds. The aim of arthropod management is to stop the population from *increasing* to the EIL. The aim of weed management, using economic thresholds as currently defined, is to temporarily *decrease* the population down to a level that is acceptable for crop production. I argue, for this reason and all those discussed above, that using the same management strategy, namely economic thresholds, for weeds and pest arthropods does not make ecological sense.

ADDITIONAL CONCEPTS

There are several other issues that are relevant to discussing the utility of thresholds for weed management. O'Donovan (1996) pointed out several of these and they are included here in abbreviated format.

Most arthropod economic thresholds are for a single species. Some authors have suggested that the interactions between different arthropod pests needs to be considered (e.g., Newsom, 1980). In the case of weeds, multiple species interactions are the norm and several authors have noted this problem (e.g., Cousens, 1987; O'Donovan, 1996). Calculating economic thresholds for a single species may not have much utility when most fields have mixed species present. Adopting NST reduces the problem of multi-species interactions at the decision making level.

In order for thresholds to be used the predictions they make must be reliable over years and locations. The weed population and yield loss components of threshold decisions are typically based on some form of regression model. Several researchers have pointed out that the various parameters in such models are proving to be unstable (Cardina, Regnier and Sparrow, 1995; Johnson et al., 1995; McGiffen et al., 1997). Utilization of an NST management philosophy reduces the significance of lack of stability of predictions.

The use of thresholds implies that the pest population can be assessed in an easy and timely manner before deciding to employ a control tactic. O'Donovan (1996) pointed out the problem of weed population assessment. Sim (1987) considered difficulty of population assessment a major reason for lack of adoption of thresholds for weed management in cereals in England, and Kwon et al. (1995) specifically excluded multi-year consideration from the PALWEED-WHEAT model due to difficulty of seedbank assessment. The actual techniques for weed population assessment are difficult (e.g., seedbank analysis), time consuming, and often require considerable expertise (recognition of seeds and/or young seedlings of several species). Associated with this are the actual costs of equipment and personnel to make the assessment. As noted previously, there is a serious problem in relation to what actually constitutes a unit of measurement. The number of seeds or seedlings present may really not be adequate for predictive purposes due to the plasticity of plant growth and the clonal nature of perennials. Biomass of weed vegetation may be a better predictor of competition and seed production but the data are difficult to obtain. Relative leaf area of crop and weeds may also be a useful way to assess weed impacts on crops but may have limited utility in predicting long-term population dynamics. Adoption of NST would probably result in reduced costs for population assessment as evaluation is on a presence/absence basis, whereas ET or EOT require development of information on density (or other parameter) per unit area. The costs of population assessment should be considered when judging the utility of using ET versus NST.

Weeds are normally present in patchy distributions (e.g., van Groenendael, 1988; Hughes, 1990; Thornton et al., 1990; O'Donovan, 1996; Cardina, Johnson and Sparrow, 1997). All authors discussed the implication of patchiness in relation to competition, crop losses, and weed population assessment. As adoption of NST requires only presence/absence information the need for evaluation of weed patchiness is reduced.

The adoption of any form of thresholds for weed management has serious implications in terms of development of resistance to herbicides in weed populations. When weeds remain in the field they produce seed, which then pass the genetic make-up of the population to the next generation. If the weeds at or below the threshold have been selected by herbicide application, then allowing them to produce seed will perpetuate the resistance characteristic. Full adoption of NST would eliminate the problem of weeds developing resistance to herbicides as no seeds are produced and thus no genes are passed on. The utility of this approach to managing a herbicide resistant weed problem has been demonstrated by Powles, Tucker and Morgan (1992) who were able to eliminate paraquat-resistant *Hordeum glaucum* Steud. in three years by eliminating seed production.

Adoption of an NST strategy implies an integrated approach to weed management, and will probably require use of hand labor to remove weeds that escape other management tactics. There are essentially no data currently available for the cost of hand weeding when weed densities are at or below the economic threshold. Estimated costs of hoeing low weed densities, and grower experiences are presented in following sections.

Land ownership may be an important reason for use of single season economic thresholds. If land is not owned but is rather farmed on short-term leases there is little incentive to consider weed seed production and the costs of weed control on a long-term basis. It is thus feasible that land-ownership is in fact a serious impediment to adoption of the sound long-term weed management programs. Landlord perception of long-term weed management problems were, however, listed as a major reason for lack of adoption of single season economic thresholds for weed management by farmers in Illinois (Czapar, Curry and Wax, 1997). The socio-economics of land ownership probably impinges on adoption of economic thresholds for weed management.

Weeds remaining at harvest were listed by farmers in Illinois as the most important reason for lack of adoption of single season economic threshold is used for weed management (Czapar, Curry and Wax, 1997). Adoption of a NST philosophy removes this concern.

POPULATION DYNAMICS RESEARCH EXAMPLES

Most research that relates crop loss to weed presence has provided little or no information on seed production, seedbank dynamics, and other aspects of the population biology of the weeds in the system (see Zimdahl, 1980). In the absence of such information I argue that it is not feasible to draw valid conclusions about what might constitute an economic threshold for the weed, because it is not possible to place the value into a pest population context in the way that entomologists have done when developing economic thresholds for arthropod management.

Elliott (1972) suggested that if a farm has a very low population of wild oats (*Avena fatua* L.) then the best management strategy would be to hand rogue to stop the formation of seeds. In 1984 I concluded, from using a simple weed population dynamics model, that the weed threshold should be zero (Norris, 1984). During the last 10 years, there have been several examples of competition studies where data for weed population dynamics were also developed and which support this concept (Table 1).

Using a corn/velvetleaf [*Abutilon theophrasti* (L.) Medic.] system in the Po valley of Italy, Zanin and Sattin (1988) and Sattin, Zanin and Berti (1992) concluded that the only logical management strategy for the weed, based on a relatively simple model of population dynamics, was to not permit the weed to produce seed. This conclusion has recently been supported for velvetleaf management in corn in the central USA (Cardina, Regnier and Sparrow, 1995; Cardina and Norquay, 1997). Légère and Deschenes (1989), working with alfalfa and oats (*Avena sativa* L.) in Quebec, Canada, concluded on the basis of weed population dynamics that hempnettle (*Galeopsis tetrahit* L.) should not be allowed to produce seed. Norris (1992a) likewise concluded that, based on population dynamics, barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] should not be permitted to set seed in sugarbeet fields in California, USA. A recent study (Akey et al., 1995b), also in California, concluded that barnyardgrass should not be allowed to set seed in processing tomato fields.

The conclusion by the authors of the papers noted above was that seed production by weeds at or below economic threshold densities was so high that it would perpetuate the need for weed control in the next crop. For velvetleaf, it was concluded that a single year of seed production by a sub-economic threshold density of the weed would result in seedling populations above the economic threshold for several years (Cardina and Norquay, 1997). From my own work (Norris, 1992a), I concluded that barnyardgrass in sugarbeets at the single season economic threshold of about 1 plant per 10 m of crop row would return about 18,000 seeds/m^2 to the seedbank, of which we now estimate that about 80% will survive to the following spring. This far exceeds the economic threshold for the weed in any crop in California. One barnyardgrass plant in a hectare of sugarbeets or tomatoes in California produces sufficient seeds to reinfest, with dispersal by human activity, the entire hectare at about 10 seeds/m^2. At 80% survival this will mandate weed control in the following crops.

The argument is made by all the above-noted authors that stopping seed production by a relatively low number of weeds in the current crop is more cost effective than controlling a large population in the next crop. I have attempted to predict costs of handweeding using current hoeing costs in California. If it is assumed that the cost of labor for hoeing is $7.50/hr, that the crew walks at about 5 km/hr when not hoeing, and that it takes 15 seconds to remove a weed, then the cost of hoeing weed densities below about 1 every 20 m of crop row does not exceed $25.00/ha. At weed densities below 1 per 100 m of crop row the cost does not exceed $10.00/ha. Even using the threshold density of 1 plant every 10 m the cost of hand weeding would only be about \$50.00/ha. These calculated values are in close agreement with \$7.50/ha provided by Mark Grewall of the J. G. Boswell Company (see below) for hoeing escape weeds in cotton (*Gossypium hirsutum* L.). Seed rain from weeds at the densities discussed here will result in the need for weed control in the subsequent crop which would cost more than the cost of hand weeding.

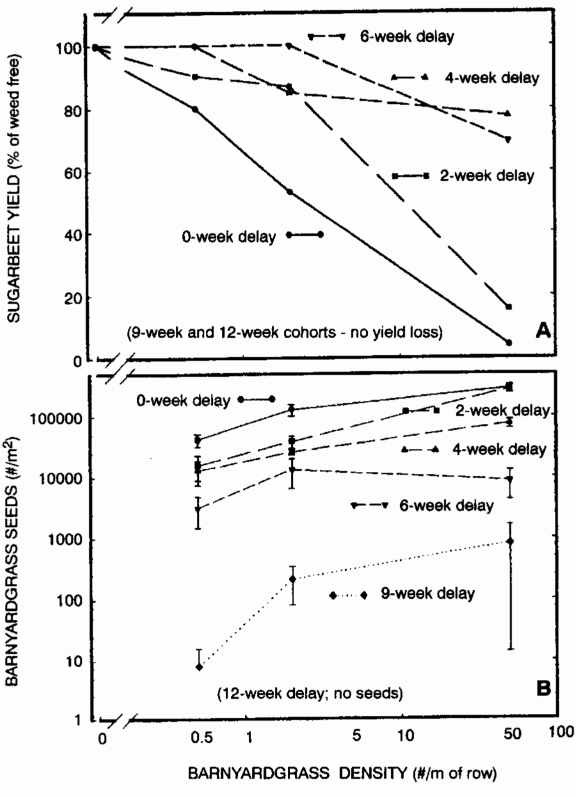
The reader is referred to the papers noted above for details of the experiments, but I feel that it is striking that when accurate data on seed production and knowledge of seedbank behavior were combined with data on economic impacts that the researchers all concluded that utilizing any form of economic thresholds as a management strategy did not make sense. I argue that current suggestions for using economic thresholds for weed management are based on crop yield loss data in the absence of weed population biology information, and thus do not properly evaluate the economic impacts of the weeds.

Wallinga and van Oijen (1997) also concluded that economic thresholds are not a sound weed management strategy. They state that "the economic underpinning of the threshold concept is deceptive and does not provide a base for rational use of weed control in the long term." They arrived at this conclusion using a strictly economic modeling approach. Their conclusion was thus the same as that derived from the field research data discussed above. This strengthens the argument that the use of economic thresholds for weed management is not appropriate.

A further set of field data has been developed that also strengthens the reason for not adopting economic thresholds. Sugarbeets were grown at the research farm at the University of California at Davis in the presence of varying densities of barnyardgrass, which was grown as cohorts initiated at varying dates after establishment of the crop. The agronomic techniques used have been described elsewhere (Norris, 1992a). Barnyardgrass was germinated with the crop, or at 2, 4, 6, 9, and 12 weeks after crop germination.

Sugarbeet yield loss resulting from the 0-delay cohort of barnyardgrass that emerged with the crop was similar to that reported previously (Norris, 1992a), and indicated that the single-season economic threshold would be about 1 weed/10 m of crop row (Figure 4A). A 2-week delay in barnyardgrass emergence in relation to the sugarbeets substantially reduced the magnitude of the crop loss, which resulted in a single-season economic threshold of about 1 plant/m. The difference between the threshold for the 0-delay versus the 2-week delay cohorts was a 10-fold increase in barnyardgrass density. A 4-week delay in barnyardgrass emergence relative to the sugarbeets increased the economic threshold density to about 3 or 4 plants/m. There were no yield losses when barnyardgrass emerged after 9 or more weeks delay regardless of weed density. In the absence of seed production information these data would suggest that after about 4 to 6 weeks there is no

FIGURE 4. Impact of increasing barnyardgrass density in relation to time of emergence on 'A' sugarbeet root yield and 'B' barnyardgrass seed production. The value listed as 'delay' indicate the time between initial sugarbeet irrigation and the first irrigation for delayed cohorts of barnyardgrass.



single-season requirement for further weed management action unless the density of the late emerging cohort was still very high.

Barnyardgrass seed production was estimated at harvest by removing inflorescences from randomly selected tillers and measuring the inflorescence lengths. This permitted prediction of seed rain based on inflorescence length and numbers (Norris, 1992c). Seed production for the 0-delay barnyardgrass cohort ranged from 40,000/m^2 for the 0.5/m density to nearly 300,000/m^2 at the high density (Figure 4B); these figures were consistent with those reported previously (Norris, 1992a). With each delay in cohort initiation the number of seeds produced decreased. At the six week delay the 0.5 and 2.0/m density were estimated to have produced 3100 and 13000 seeds/m^2, respectively. At these densities for this delay in initiation there was no economic yield loss, yet the seed production was sufficient to cause major problems in the next crop. Even at the 9-week initiation delay there was sufficient seed production to resupply much of the seedbank yet there was no economic impact on the current crop yield. These data for seed production by late emerging cohorts of barnyardgrass again suggest that the single season economic thresholds would be a poor way to manage the weed due to the number of seeds produced by sub-threshold densities of the weed.

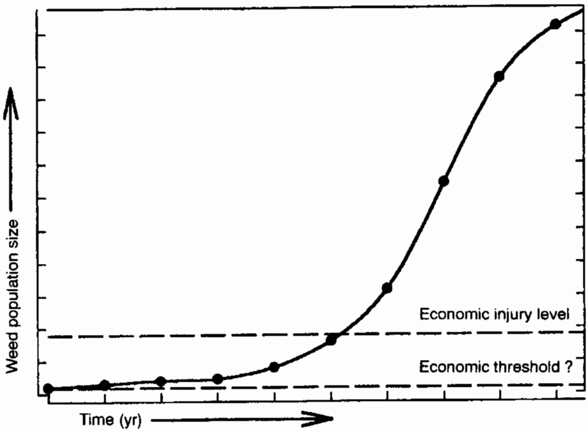
WEED INVASIONS AND THE THRESHOLD CONCEPT

Dewey, Jenkins and Tonioli (1995) proposed that invading noxious weed species should be treated like a "wildfire." The implication is that control should be carried out while the "fire" is small, rather than attempting control when it has become a large conflagration. This is the accepted paradigm for fighting wildfires. Control costs are much lower when a wildfire is controlled early. One could say that we have a very low threshold for wildfires. In the context of weed management this could be rephrased to state that the threshold for invading species is low; controlling a few plants is much less costly than controlling many well established plants.

Non-critical acceptance of the single season economic threshold concept is *the* most important problem in relation to weed invasion. Most land managers do not act until the problem caused by an invading weed reaches the EIL (Figure 5), at which time a seedbank has already been established. Even using EOT, or ET as defined entomologically, would mean treatment when the population is low. The NST approach would suggest that newly established individual plants should be removed prior to seed production. Such action would stop the plant from developing a seedbank.

Velvetleaf makes a good example to illustrate the point made above. Hand rogueing of the weed is fairly easy in most crops when the populations are low. Cardina and Norquay (1997) determined that a single year of seed production from a sub-threshold velvetleaf population results in seedling populations well above the threshold level in following years. Allowing the plant to produce seed results in a very long lived weed problem (Figure 6); even with no reseeding there were adequate seeds remaining in the soil to create a new infestation even after 17 years of corn and soybean production, and even more if alfalfa had been grown (Lueschen et al., 1993). The use of ET, as defined by weed science, is a disastrous approach to managing invading species that leads to increased costs and reduced production. The use of NST is the logical threshold to use for management of invading species that is

FIGURE 5. Hypothetical increase in population for an invading weed species, shown in relation to economic injury level and economic threshold used in the accepted entomological sense. Economic injury level is population at which economic loss starts to occur; economic threshold (?) is the population at which control measures should be initiated.



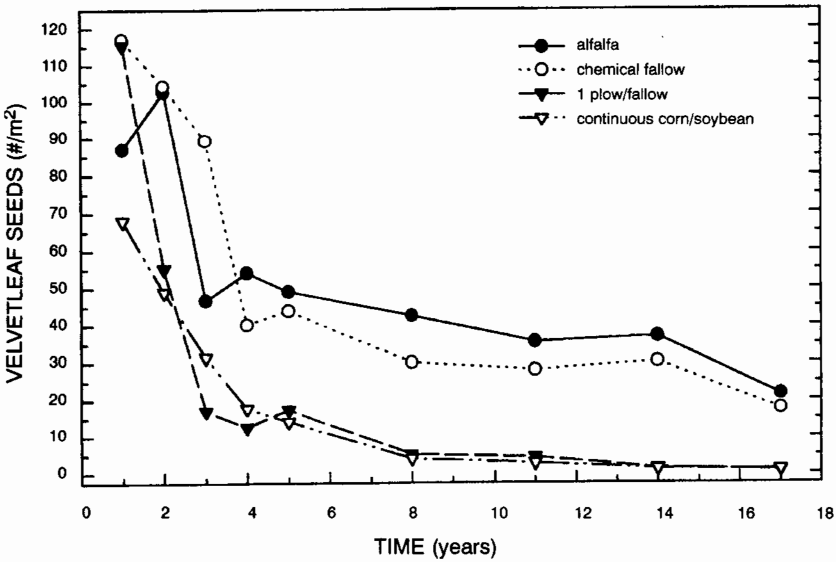
spread by human activity. Adoption of ET may, however, be the only logical approach to managing an invading species with wind born seeds.

USE OF NO SEED THRESHOLDS FOR WEED MANAGEMENT: FARM EXAMPLES IN CALIFORNIA

Although anecdotal in nature, weed management programs used by two California farms serve as practical examples of the advantages of adopting policies that do not permit weeds to produce seed. The farm managers refuse to use thresholds for weed management, although they subscribe to and use thresholds for management of other types of pests. They argue that the use of thresholds for weed management would not be economically acceptable due to the long-term problems created by letting weeds set seed, and which thus perpetuate the seedbank.

One example is the largest arable corporate farm in California (J. G. Boswell Co., 60,000 ha of arable crop production) (see article by Horstmeier, 1995). The whole farm has been operated on a policy of not letting weeds set seed for over 40 years. They still use hand weeding in 30,000 ha of cotton two or three times a season to ensure that weeds like nightshade (*Solanum* spp.) and annual morning glory (*Ipomoea* spp.) do not produce seed. When I

FIGURE 6. Decline of velvetleaf seedbank over time in relation to different cultural practice. Graph is redrawn from data presented by Lueschen et al. (1993).



asked Mr. Grewal, the manager described in the above-mentioned article (Horstmeier, 1995), how he could afford the hand weeding his response was "how can I afford not to?" What Mr. Grewal meant was that he judged the $5 or $6 per hectare cost of hand weeding to be cheaper than controlling a large weed population in the next season. This is a very different paradigm than that of the visual economic threshold that most farmers appear to use. Mr. Grewal states that weed management costs for the Boswell farming operation are lower than those for their competitors. The Boswell Company philosophy emphasizes a holistic approach to weed management that most farms never actually practice. The following are some examples of such practices: farm machinery *is* cleaned when it leaves fields in which weeds were present; weeds are not allowed to set seed when present in crop stubble following harvest; weeds are not permitted to grow on field margins, roadsides and ditchbanks; all equipment storage areas are maintained free of weeds; drivers of harvesters are instructed to go around isolated infestations of weeds so that they do not spread the seed.

Another example is a 180 ha intensive vegetable farm in the Salinas valley.

Louis Manzoni felt that weed management was becoming so difficult in vegetable production that he decided to kill the weed seedbank by treating the whole ranch with methyl bromide (done over several years). The single treatment coupled with the change in weed management philosophy to NST has allowed Mr. Manzoni to grow vegetable crops without using herbicides since that time. Seven years after using methyl bromide, Mr. Manzoni had essentially no weeds present on the ranch. He is so adamant that weeds should not set seed that he even uses a hand crew, at a cost that he estimated to be over $150/ha, to pull weeds out of a berseem clover (*Trifolium alexandrinum* L.) cover crop! Mr. Manzoni informed me that he can obtain contracts with packer/shippers for his vegetable production much more easily now that his weed management has changed to NST. Mr. Manzoni states that he recovered the cost of the methyl bromide in four crops (2 years) and that since that time his weed control costs have been much lower than before he adopted NST. Mr. Manzoni considers that his neighbors who permit weeds to set seed in their crops or along the margins of fields are "crazy."

These farms represent two different arable agro-ecosystems, yet both claim that their weed management costs are lower than their neighbors (competitors?) who use one or other form of thresholds (or let at least some weeds go to seed). The weed management programs for the two farm examples have changed from a concept of control to achieve a successful crop, to a strategy aimed at stopping weed reinfestation. Both farms are owned, not leased, and both managers point out that there is incentive for using long-term weed management strategies. This suggests that the weed management paradigm used by most farmers is substantially contributing to their continuing weed problems and relatively high levels of weed management required each year, and strengthens the argument proposed by the researchers who have arrived at the same conclusions through combination of crop loss and weed population biology research (Table 1).

Until the research community develops reliable data on the long-term impacts of different weed management paradigms on weed population dynamics and farm economics, we will have to be satisfied with accepting that the strategies used by some of our progressive farmers may be correct.

CONCLUSION

In light of ecological principles of population biology, in light of mounting weed population biology research evidence in relation to economic losses, in light of revised thinking about weed invasion processes, and in light of progressive farmer experiences there is strong reason to reject use of single season economic thresholds for weed management. The only debate that should be going on is between using multi-year economic thresholds (EOT) as proposed by Cousens (1987) and exemplified by work by Doyle, Cousens and Moss (1986) and by Bauer and Mortensen (1992), or adopting the policy of not letting weeds set seed as proposed for velvetleaf in corn (Zanin and Sattin, 1988; Sattin, Zanin and Berti, 1992; Cardina, Regnier and Sparrow, 1995; Cardina and Norquay, 1997), hempnettle in alfalfa and oats (Légère and Deschenes, 1989), barnyardgrass in sugarbeets (Norris, 1992a), and barnyardgrass in tomatoes (Akey et al., 1995a). The ultimate utility of using thresholds for weed management cannot be resolved without data from long-term research that provides reliable economic information in relation to weed management practice coupled with information on the population dynamics of the weeds. I therefore argue that there is urgent need for weed science to develop reliable data that couples weed population biology with crop losses caused by weeds.

I also argue that there is need to develop a weed management paradigm, and not to blindly accept that developed for management of arthropod pests. If we continue to pursue a weed management paradigm that uses single-season economic thresholds we are probably doomed to continue using large quantities of herbicides and to face ever increasing problems of herbicide resistant weeds. If a no seed threshold weed management paradigm is adopted, weed control costs should ultimately decrease, and reliance on herbicides to "put out the fire" each year will also decrease. I also strongly believe that weed science also needs to reevaluate the trend away from use of hand labor for weed management, as it is this tactic which makes NST work. The development of "smart" sprayers that can detect the presence of a weed have the potential to greatly increase the ease of implementing an NST philosophy in the future. If we adopt no seed thresholds based on integrated weed management practices, the whole problem of resistant weeds should decrease; if no seed are produced, then no resistance genes are passed to the next generation.

REFERENCES

Akey, W.C., R.F. Norris, M. Rejmanek, and C.L. Elmore. (1995a). Does it matter where the weeds are? The impact of plant aggregation on interspecific competition. *Weed Sci. Soc. Am. Abst.* 35: 48.

Akey, W.C., R.F. Norris, M. Rejmanek, and C.L. Elmore. (1995b). Influence of density and spatial distribution of barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] on its growth and seed production in competition with direct seeded tomatoes. *Weed Sci. Soc. Am. Abst.* 35: 48.

Auld, B.A., K.M. Menz, and C.A. Tisdell (1987). *Weed Control Economics.* London, NW1 7DX, UK: Academic Press (London) Ltd.

Auld, B.A. and C.A. Tisdell. (1987). Economic thresholds and response to uncertainty in weed control. *Agricultural Systems* 25: 219-227.

Bauer, T.A. and D.A. Mortensen. (1992). A comparison of economic and economic optimum thresholds for two annual weeds in soybeans. *Weed Technology* 6: 228-235.
Berti, A., C. Dunan, M. Sattin, G. Zanin, and P. Westra. (1996). A new approach to determine when to control weeds. *Weed Science* 44: 496-503.
Black, I.D. and C.B. Dyson. (1993). An economic threshold model for spraying herbicides in cereals. *Weed Research* 33: 279-290.
Bosnic, A.C. and C.J. Swanton. (1997). Economic decision rules for postemergence herbicide control of barnyardgrass (*Echinochloa crus-galli*) in corn (*Zea mays*). *Weed Science* 45: 557-563.
Burnside, O.C., R.G. Wilson, S. Weisberg, and K.G. Hubbard. (1996). Seed longevity of 41 weed species buried 17 years in eastern and western Nebraska. *Weed Sci* 44: 74-86.
Cardina, J., G.A. Johnson, and D.H. Sparrow. (1997). The nature and consequence of weed spatial distribution. *Weed Science* 45: 364-373.
Cardina, J. and H.M. Norquay. (1997). Seed production and seedbank dynamics in subthreshold velvetleaf (*Abutilon theophrasti*) populations. *Weed Science* 45: 85-90.
Cardina, J., E. Regnier, and D. Sparrow. (1995). Velvetleaf (*Abutilon theophrasti*) competition and economic thresholds in conventional- and no-tillage corn (*Zea mays*). *Weed Science* 43: 81-87.
Coble, H.D. (1985). Development and implementation of economic thresholds for soybean. *Integrated Pest Management on Major Agricultural Systems,* eds. R.E. Frisbie and P.L. Adkisson. College Station, TX: Texas A&M University. MP-1616, pp. 285-307.
Coble, H.D. and D.A. Mortensen. (1992). The threshold concept and its application to weed science. *Weed Technology* 6: 191-195.
Cousens, R. (1987). Theory and reality of weed control thresholds. *Plant Protection Quarterly* 2: 13-20.
Cousens, R., C., J. Doyle, B.J. Wilson, and G.W. Cussans. (1986). Modelling the economics of controlling *Avena fatua* in winter wheat. *Pesticide Science* 17: 1-12.
Cousens, R., B.J. Wilson, and G.W. Cussans (1985). *To Spray or Not to Spray: The Theory Behind the Practice.* British Crop Protection Conference-Weeds, Brighton, U.K., pp. 671-678.
Cussans, G.W., R.D. Cousens, and B. Wilson, J. (1986). Thresholds for weed control–the concepts and their interpretation. *Proc. EWRS Symp. 1986. Economic Weed Control* pp:253-260.
Czapar, G.F., M.P. Curry, and L.M. Wax. (1997). Grower acceptance of economic thresholds for weed management in Illinois. *Weed Technology* 11: 828-831.
Dewey, S.A., M.J. Jenkins, and R.C. Tonioli. (1995). Wildfire suppression–a paradigm for noxious weed management. *Weed Technology* 9: 621-627.
Doyle, C.J. (1991). Mathematical models in weed management. *Crop Protection* 10:432-444.
Doyle, C.J., R. Cousens, and S.R. Moss. (1986). A model of the economics of controlling *Alopecurus myosuroides* Huds. in winter wheat. *Crop Protection* 5: 143-150.

Dunan, C.M., P. Westra, E.E. Schweizer, D.W. Lybecker, and F.D. Moore. (1995). The concept and application of early economic period threshold–the case of DCPA in onions (*Allium cepa*). *Weed Science* 43: 634-639.
Elliott, J.G. (1972). *Wild Oats, Where Next?* Proceedings British Weed Control Conference, Brighton, U.K., pp. 965-976.
Ferris, H. (1978). Nematode economic thresholds: derivations, requirements, and theoretical considerations. *Journal of Nematology* 10: 341-350.
Gerowitt, B. and R. Heitefuss. (1990). Weed economic thresholds in cereals in the Federal Republic of Germany. *Crop Protection* 9: 323-331.
Heitefuss, R., B. Gerowitt, and W. Wahmoff (1987). *Development and Implementation of Weed Economic Thresholds in the F. R. Germany.* British Crop Protection Conference–Weeds., pp. 1025-1033.
Horstmeier, G. (1995). Not one weed. *Top Producer*: 26-27.
Hughes, G. (1990). The problem of weed patchiness. *Weed Research* 30:223-224.
Johnson, G.A., D.A. Mortensen, L.J. Young, and A.R. Martin. (1995). The stability of weed seedling population models and parameters in Eastern Nebraska corn (*Zea mays*) and soybean (*Glycine max*) fields. *Weed Science* 43: 604-611.
Jordan, N. (1992). Weed demography and population dynamics: implications for threshold management. *Weed Technology* 6: 184-190.
Kwon, T.J., D.L. Young, F.L. Young, and C.M. Boerboom. (1995). PALWEED-WHEAT: a bioeconomic decision model for postemergence weed management in winter wheat (*Triticum aestivum*). *Weed Science* 43: 595-603.
Légère, A. and J.-M. Deschenes. (1989). Effects of time of emergence, population density and interspecific competition on hemp-nettle (*Galeopsis tetrahit*) seed production. *Canadian Journal of Plant Science* 69: 185-194.
Lueschen, W.E., R.N. Anderson, T.R. Hoverstad, and B.K. Kann. (1993). Seventeen years of cropping systems and tillage affect velvetleaf (*Abutilon theophrasti*) seed longevity. *Weed Science* 41: 82-86.
Lybecker, D.W., E.E. Schweizer, and R.P. King. (1991). Weed management decisions in corn based on bioeconomic modeling. *Weed Science* 39:124-129.
McGiffen, M.E., F. Forcella, M.J. Lindstrom, and D.C. Reicosky. (1997). Covariance of cropping systems and foxtail density as predictors of weed interference. *Weed Science* 45: 388-396.
Newsom, L.D. (1980). The next rung up the integrated pest management ladder. *Entomological Society of America Bulletin* 26: 369-374.
Norris, R.F. (1984). Weed thresholds in relation to long-term population dynamics. *Proceedings of the Western Society of Weed Science* 37: 38-44.
Norris, R.F. (1992a). Case history for weed competition/population ecology: barnyardgrass (*Echinochloa crus-galli*) in sugarbeets (*Beta vulgaris*). *Weed Technology* 6: 220-227.
Norris, R.F. (1992b). *Have Ecological and Biological Studies Improved Weed Control Strategies?* Proceedings of the First International Weed Control Congress, Melbourne, Australia, pp. 7-33.
Norris, R.F. (1992c). *Predicting Seed Rain in Barnyardgrass (Echinochloa crus-galli).* IX Colloquium on Weed Biology and Ecology, Dijon, France, European Weed Research Society, pp. 377-386.

Norris, R.F. (1995). Thresholds: detrimental for weed management? *European Journal of Plant Pathology, Abstracts*: 969.

O'Donovan, J.T. (1996). Weed economic thresholds: useful agronomic tool or pipe dream? *Phytoprotection* 77: 13-28.

Osteen, C.D., J. Moffitt, and A.W. Johnson. (1988). Risk efficient action thresholds for nematode management. *Journal of Production Agriculture* 1: 332-338.

Pedigo, L.P. (1996). *Entomology & Pest Management.* Upper Saddle River, NJ: Prentice Hall.

Pedigo, L.P., S.H. Hutchins, and L.G. Higley. (1986). Economic injury levels in theory and practice. *Annual Review of Entomology* 31: 341-368.

Powles, S.B., E.S. Tucker, and T.R. Morgan. (1992). Eradication of paraquat-resistant *Hordeum glaucum* Steud. by prevention of seed production for 3 years. *Weed Research* 32: 207-211.

Radosevich, S., J. Holt, and C. Ghersa (1997). *Weed Ecology: Implications for Management.* New York, NY: John Wiley and Sons, Inc.

Renner, K.A. and J.R. Black. (1991). SOYHERB–A computer program for soybean herbicide decision making. *Agronomy Journal* 83: 921-925.

Sattin, M., G. Zanin, and A. Berti. (1992). Case history for weed competition/population ecology: velvetleaf (*Abutilon theophrasti*) in corn (*Zea mays*). *Weed Technology* 6: 213-219.

Sim, L.C. (1987). *The Value and Practicality of Using Weed Thresholds in the Field.* British Crop Protection Conference–Weeds., Brighton, U.K., pp. 1067-1071.

Stern, V.M. (1973). Economic thresholds. *Annual Review of Entomology* 18: 259-280.

Stern, V.M., R.F. Smith, R. van den Bosch, and K.S. Hagen. (1959). The integrated control concept. *Hilgardia* 29: 81-99.

Thompson, K., S.R. Band, and J.G. Hodgson. (1993). Seed size and shape predict persistence in the soil. *Functional Ecology* 7: 236-241.

Thornton, P.K., R.H. Fawcett, J.B. Dent, and T.J. Perkins. (1990). Spatial weed distribution and economic thresholds for weed control. *Crop Protection* 9: 337-342.

van Groenendael, J.M. (1988). Patchy distribution of weeds and some implications for modelling population dynamics. *Weed Research* 28: 437-441.

Wallinga, J. and M. van Oijen. (1997). Level of threshold weed density does not affect the long-term frequency of weed control. *Crop Protection* 16: 273-278.

Weersink, A., W. Deen, and S. Weaver. (1991). Defining and measuring economic threshold levels. *Canadian Journal of Agricultural Economics* 39: 619-625.

Wilkerson, G.G., S.A. Modena, and H.D. Coble. (1991). HERB: decision model for postemergence weed control in soybean. *Agronomy Journal* 83: 413-417.

Wilson, B.J. and H.M. Lawson. (1992). Seedbank persistence and seedling emergence of seven weed species in autumn-sown crops following a single years seeding. *Annals of Applied Biology* 120: 105-116.

Zadoks, J.C. (1985). On the conceptual basis of crop loss assessment: the threshold theory. *Review of Phytopathology* 23: 455-473.

Zanin, G., A. Berti, and L. Toniolo. (1993). Estimation of economic thresholds for weed control in winter wheat. *Weed Research* 33: 459-467.

Zanin, G. and M. Sattin. (1988). Threshold level and seed production of velvetleaf (*Abutilon theophrasti* Medicus) in maize. *Weed Research* 28: 347-352.
Zimdahl, R.L. (1980). *Weed-Crop Competition: A Review.* Corvallis, OR.: International Plant Protection Center, Orgeon State University.

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