INTERFERENCE BETWEEN PIGWEED (*Amaranthus* spp.), BARNYARDGRASS
(*Echinochloa crus-galli* L. Beauv.), AND SOYBEAN (*Glycine max* L. Merr);
ENCOMPASSING A MULTI-SPECIES APPROACH.

A Thesis
Presented to
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of
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by
PAUL COWAN

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INTERFERENCE BETWEEN PIGWEED (Amaranthus spp.),
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Field experiments were conducted to determine; the influence of time of
emergence and density of single and multi-species populations of pigweed and
barnyardgrass on soybean yield and competitive abilities of pigweed and
barnyardgrass. Pigweed and barnyardgrass were established at selected
densities within 12.5 cm on either side of the soybean row. Pigweed and
barnyardgrass seeds were sown concurrently with soybean and at the cotyledon
stage of soybean growth. Time and density of pigweed and barnyardgrass
seedling emergence relative to soybean influenced the magnitude of soybean
yield loss. Maximum soybean yield loss ranged from 32 to 99%, depending
upon time of emergence relative to soybean. Pigweed was more competitive
than barnyardgrass across all locations, years, and time of weed emergence.
When pigweed was assigned a competitive index of 1.0 on a scale from 0 to 1,
the competitive ability of barnyardgrass ranged from 0.075 to 0.40 of pigweed,
depending upon location and time of emergence. Competitive indexing studies
must be conducted in combination with a crop under differing environmental conditions.
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INTRODUCTION

An integrated weed management system (IWM) is imperative for modern agriculture to remain a sustainable enterprise. One of the primary objectives of an integrated weed management system is to increase the efficiency of herbicide use and to reduce the amount of herbicides applied into the environment. Herbicides remain an invaluable component of growers' weed control programs, but in order to reduce our dependence upon them, they should be used in conjunction with other IWM strategies.

Weed biology, weed competitive ability, and weed threshold information is currently being expanded to assist producers with their herbicide selection, rate, timing, and application. This information is also crucial for the ongoing development of crop-weed competition models. Crop-weed competition models attempt to combine many factors to determine crop yield loss caused by weeds and if control measures such as additional herbicide applications are needed over the short- and long-term. In many instances, weeds that have escaped a pre-emergence herbicide application, do not cause a significant crop yield loss.

Growers' fields commonly host many different weed species. Weeds can compete against each other as well as against a crop. Current weed thresholds and competition models can only account for a single weed species in any given field situation. Expanding weed biology, weed competitive ability, and weed
threshold information to include multiple weed species is the next step in the
development of crop-weed competition models, and the evolution of an IWM
system for today's farmer.
Integrated Weed Management.

Weed management is essential for a profitable agricultural system. During the era of agricultural industrialization, herbicides had been relied on as one of the primary tools for managing weed populations. The extensive use of herbicides was one of the main reasons that an abundant and economical food supply has been maintained in agriculturally developed nations (Coble 1994; Kropff and Lotz 1992). However, increasing herbicide resistance in certain weeds, rising herbicide and other input costs, and widespread concern about the environmental impacts of herbicides has resulted in greater pressure on producers to reduce the use of herbicides (Kropff and Lotz 1992).

We are now in the midst of the post-industrial era of agricultural production. Today’s agricultural weed management strategies require a “systems approach”. A systems approach to farm weed management implies that each weed control decision be evaluated in terms of its impact on the performance of the farming system as a whole (Ikerd 1993). Integrated weed management (IWM) represents a systems approach (Swanton and Murphy 1996). IWM incorporates crop breeding, fertilization, rotation, chemical weed control, mechanical weed control, competition, successional management, and soil management into a method of reducing weed interference while maintaining
acceptable crop yields (Swanton and Weise 1991; Thill et al. 1991). IWM is designed to be economically, environmentally, and socially acceptable (Swanton and Murphy 1996).

IWM is not a new concept. Many farmers have been using some form of IWM systems approach to control weeds since the turn of the century (Elmore 1996; Thill et al. 1991). Before the advent of chemical weed control, growers relied on a combination of weed control tactics such as tillage, crop planting pattern, and crop rotation. Development of chemicals for weed control in the middle of the 20th century was one of the most significant advancements in agricultural science (Coble 1994). It is not surprising that growers became dependant upon chemicals as their only defense against weeds. Researchers over the past two decades have been trying to decrease chemical usage by re-introducing the IWM concept to today’s farmer. This does not mean that herbicides are not important components of an IWM system. Herbicides will likely continue to be an important weed management tool. However, a fully integrated weed management system will include a plethora of techniques that will optimize herbicide use for weed control (Coble 1994; Elmore 1996; Swanton and Murphy 1996; Thill et al. 1991).

Swanton and Murphy (1996) developed a conceptual framework relating the general components of IWM (soil and ground cover management, crop and nutrient management, predictive crop-weed modelling) to agroecosystem health. Predicting the outcome of crop-weed interference is a significant part of an IWM
system. Models attempt to combine many factors to determine crop yield loss caused by weeds and if control measures are needed over the short- and long-term (Kropff and Lotz 1992; Swanton and Weise 1991). They represent an opportunity to shift weed science from a descriptive to a predictive approach.

**Critical Period of Weed Control.**

An initial step in the development of an IWM system is to define the period during which weeds must be controlled to minimize yield loss. Historically, two components of the critical period of weed control have been recognized (Everaarts 1992; Hall et al. 1992; Stoller et al. 1987; Van Acker et al. 1993; Weaver and Tan 1983). The first component is the critical weed-free period. It is the maximum length of time weeds emerging with a crop can be allowed to grow until they begin to cause unacceptable crop yield losses (Hall et al. 1992; Van Acker et al. 1993; Weaver and Tan 1983). Van Acker et al. (1993) found that a period of weed control lasting up to the fourth node growth stage (V4), approximately 30 days after emergence, was adequate to prevent a soybean (*Glycine max* (L.) Merr.) yield loss of more than 2.5%. Hall et al. (1992) concluded that field corn (*Zea mays* L.) kept weed-free for approximately 34 days after or until the 8-10 leaf stage would only incur a 5% yield loss.

The second component is the critical weed removal period. This is the minimum length of time weeds that emerge with a crop can remain before unacceptable crop yield losses occur (Hall et al. 1992; Van Acker et al. 1993; Weaver and Tan 1983). The time of weed removal is variable and was
demonstrated to be from the V3 to R4 stage in soybean, and from the 10-14 leaf stage of field corn by Van Acker et al. (1993) and Hall et al. (1992) respectively. Critical periods of weed control have also been established for other crops such as transplanted tomatoes (*Lycopersicon esculentum* Mill.) (Weaver and Tan 1983), white beans (*Phaseolus vulgaris* L.) (Woolley et al. 1993), onions (*Allium cepa* L.) (Hewson and Roberts 1971), potatoes (*Solanum tuberosum* L.) (Everaarts and Satsyati 1977), cassava (*Manihot esculenta* L. Crantz.) (Onochie 1975), sugarbeet (*Beta vulgaris* L.) (Kropff 1988), cabbage (*Brassica oleracea* var. *capitata* L.), pickling cucumbers (*Cucumis sativus* L.), and field-seeded tomatoes (Weaver 1984). Information generated from critical period studies may lead to less reliance on the use of long term residual herbicides, and more reliance on accurately timed post-emergent herbicide applications (Weaver and Tan 1983).

**Weed Thresholds.**

The implementation of weed thresholds is the second integral component of an IWM system. Weed thresholds help agricultural producers determine the necessity and timing of herbicide applications (Knezevic et al. 1994; Swanton and Weise 1991).

There are generally two types of weed thresholds; competitive and economic. A competitive threshold can be defined from field research data as the weed density above which crop yield is reduced by an unacceptable amount, usually 10 to 20% (Oliver 1988). Economic thresholds are defined as the weed
density at which the benefit derived from herbicide application equals the cost of control (Bauer and Mortensen 1992; Oliver 1988; Weaver 1991). Weed economic threshold models are strongly linked to the critical period of weed control concept. Critical periods of weed control indicate when herbicides are needed. Weed economic threshold models determine if weed density is sufficient to warrant control measures such as an additional herbicide application during the critical period (Coble and Mortensen 1992; Swanton and Murphy 1996). Using weed economic threshold models will help eliminate unnecessary input costs for weed control (Coble 1994; Swanton and Murphy 1996).

In most quantitative studies on crop-weed interference, empirical models have been developed to describe the impact of weed populations on crop yield, and subsequently generate competitive and economic weed thresholds. The majority of the modelling research on crop-weed interference has involved a single timing of weed emergence. It has been demonstrated that weed emergence relative to the crop may be more important in determining the impact of weeds on crop yield than weed density alone (Chikoye and Swanton 1995; Knezevic et al. 1995; Kropff 1988; O'Donovan et al. 1985). Empirical modelling research has more recently expanded to incorporate multiple times of weed emergence into the crop-weed interference equation. These two types of empirical based models have been the focal point for the development of both competitive and economic single weed species thresholds.
Competitive Weed Thresholds. There have been numerous reports on competitive weed thresholds possessing a single time of weed emergence within a variety of field crops. Corn and soybean are consistently the two most commonly studied crops in all facets of threshold research. Moolani et al. (1964) was one of the first to document crop-weed interference in the context of a competitive threshold. They documented that 4 smooth pigweed (*Amaranthus hybridus* L. # AMACH) plants per metre of row reduced yield loss in corn and soybean by 15 and 32%, respectively. At densities of 16 weeds per 10 m of row, redroot pigweed (*Amaranthus retroflexus* L. # AMARE) caused a soybean yield reduction of 22%, compared to 15% by common lambsquarters (*Chenopodium album* L. # CHEAL), 12% by common ragweed (*Ambrosia artemisiifolia* L. # AMBEL), and 5% by sicklepod (*Cassia obtusifolia* L. # CASOB) (Shurtleff and Coble 1985). In the same study, common cocklebur (*Xanthium strumarium* L. # XANST) at 0.8 plants per m of row caused an 11% soybean yield loss. Oliver (1988) confirmed the results of Shurtleff and Coble (1985) in that 0.33 common cocklebur plants per metre of row reduced soybean yield loss by 13%. Coble (1981) demonstrated that soybean yield loss was reduced 8% by 0.4 common ragweed plants per m of row. Barnyardgrass (*Echinochloa crus-galli* (L.) Beauv. # ECHCG) at a density of 42 plants per m of row reduced soybean yield by 10% (Vail and Oliver 1993). The competitive threshold for jimsonweed (*Datura stramonium* L. # DATST) in soybean has been documented at 1-3 plants per m² (Hagwood, Jr. et al. 1981; Kirkpatrick et al. 1983; Weaver 1986).
Corn yield was reduced 27, 12, 18, and 22% by common cocklebur, common lambsquarters, giant foxtail (Setaria faberi Hermm. # SETFA), and shattercane (Sorghum bicolor L. Moench # SORVU) at densities of 4.7, 4.9, 65.0 and 20.0 plants per m of row, respectively (Beckett et al. 1988). Green foxtail (Setaria viridis (L.) Beauv # SETVI) and common lambsquarters densities from 89 to 119 and 83 to 221 plants m², reduced corn yield by 5.8 to 17.6, and 12.3 to 37.9%, respectively (Sibuga and Bandeen 1980). A maximum density of 3 rhizome johnsongrass (Sorghum halepense (L.) Pers. # SOLHA) plants per 9.8 m of row was considered critical to avoid corn yield losses greater than 5% (Ghosheh et al. 1996). Lindquist et al. (1996) documented that extremely low densities (approaching 1 plant per m of row) of velvetleaf (Abutilon theophrasti Medic. # ABUTH) can cause corn yield losses from 3 to 14%.

Competitive weed thresholds with a single time of weed emergence have also been chronicled in a variety of other crops. Barnyardgrass at 10 plants per m of row caused an 80% root yield loss in sugarbeets (Norris 1992). To reduce yield of sugar beet roots by 10 to 12%, required 9 to 11 Powell amaranth (Amaranthus powelli S. Wats. # AMAPO) plants per 30 m of row in 1982 and 1983, respectively (Schweizer and Lauridson 1985). Total and marketable potato tuber yields were reduced by green foxtail densities of less than 75 plants per m². Densities of 48 redroot pigweed and common cocklebur plants per 7.31 m of row reduced cotton (Gossypium hirsutum L.) yields by 50 and 80%, respectively (Buchanan and Burns 1971). Buchanan et al. (1980a) later
documented that densities of 2 redroot pigweed and sicklepod plants per 15 m of row reduced cotton yield by 10.0 and 7.7%, respectively. Fifty green foxtail plants m² reduced total potato tuber yields between 20 and 50%, when the weed emerged 4 to 8 days prior to crop emergence (Wall and Friesen 1990). Bhowmik and Reddy (1988) found that season-long interference of barnyardgrass reduced marketable tomato fruit number and weight at all densities compared to weed-free plots. Reductions ranged from 26 to 84%, at densities of 16 and 64 plants per m of row, respectively. Twenty nightshade (Solanum ptycanthum Dun. # SOLPT; S. sarrachoides Sendt. # SOLSA) plants per m of row reduced yields of transplanted and field-seeded tomatoes by 30 and 95%, respectively (Weaver et al. 1987). Mixtures of redroot pigweed and prostrate pigweed (Amaranthus blitoides L. # AMABL) competing with transplanted tomato for the entire growing season reduced yield up to 83 and 68% in 1990 and 1991, respectively (Qasem 1992). Established horse nettle (Solanum carolinense L. # SOLCA) plants at a density of 16 plants per 4.6 m of row reduced snap bean (Phaseolus vulgaris L.) yield by 55% (Frank 1990). Cultivated oat (Avena sativa L. # AVESA) as a weed species caused a yield loss of 5% at densities of 27, 38, 6, 9, and 4 plants per m² in barley (Hordeum vulgare L.), rape (Brassica napus L.), field bean (Vicia faba L.), peas (Pisum sativum L.), and flax (Linum usitatissimum L.), respectively, when emerging with the crops (Lutman et al. 1996). At densities of 100 plants per m², wheat (Triticum aestivum L.) yields in Australia were decreased 32% by wild oat (Avena
fatua L. # AVEFA) (Gill et al. 1986), 30% by ripgut brome grass (Bromus
diandrus Roth. # BRODI)(Gill et al. 1987), 24% by hare barley grass (Hordueum
leporinum Link. # HORLE)(Poole et al. 1986), 8 to 20% by annual ryegrass
(Lolium rigidum Gaud.)(Gill and Poole 1986), and 25 to 35% by wild radish
(Raphanus raphanistrum L. # RAPRA)(Moore 1979).

The inclusion of multiple times of weed emergence into competitive weed
thresholds is a vital component for improving the predictive ability of empirical
models. Dew (1972) suggested that the relative time of emergence of wild oat
within a wheat crop would affect the severity of yield loss. Hagwood et al. (1981)
determined that jimsonweed emerging at the fourth trifoliate leaf stage of
soybean did not compete effectively and subsequently did not reduce soybean
growth or yield. Yield losses in wheat and barley increased approximately 3%
for every day wild oat emerged before the crop. Yield losses diminished by the
same amount for every day wild oat emerged after the crop (O’Donovan et al.
1985). Downy brome (Bromus tectorum L. # BROTE) densities of 24, 40, and 65
per m² reduced winter wheat yield by 10, 15, and 20%, respectively, when
weeds emerged within 14 days after wheat emergence (Stahlman and Miller
1990). Redroot pigweed, pitted morningglory (Ipomea lacunosa L. # IPOLA),
and prickly sida (Sida spinosa L. # SIDSP) emerging with a cotton crop have
been shown to reduce yields to a greater extent than when emerging 4 weeks
later (Buchanan et al. 1980b). As few as 1 barnyardgrass or redroot pigweed
per m of row reduced marketable potato tuber yield 19 to 33%, when seeded in
the row at the time of potato planting, compared to 0% with 4 pigweed or barnyardgrass plants per m of row emerging at hilling (6-7 weeks after planting) (Vangessel and Renner 1990). Kropff (1988) documented that common lambsquarters emerging with sugarbeet at densities of 5.5 and 22 plants m², reduced crop yield by 79 and 93%, respectively. Common lambsquarters emerging 21 days after sugarbeet at a density of 9.1 plants m² reduced crop yield by only 7%.

There have been numerous competitive weed thresholds with multiple times of weed emergence documented in Ontario. A density of 0.5 redroot pigweed per m of row emerging with a corn crop and 4 redroot pigweed per m of row emerging between the 4- and 7-leaf stage of corn reduced corn yield by 5% (Knezevic et al. 1994). Estimated soybean yield losses decreased from 16.4 to 0.5% with delayed pigweed emergence from 0 to 20 degree days (Dieleman et al. 1995). Chikoye et al. (1995) documented that when 1.5 common ragweed seedlings per m of row emerged with a white bean crop, 10 to 22% seed yield loss occurred. Yield losses of 4 to 9% occurred when the same common ragweed density emerged at the second trifoliate stage of white bean. Bosnic et al. (1997b) observed that maximum corn grain yield loss ranged from 26 to 35% for barnyardgrass emerging with the crop, and less than 6% crop yield loss when barnyardgrass seedlings emerge after the 4-leaf stage of corn. Competitive weed threshold models that incorporate time of weed emergence represent a step toward improving predictions of yield loss.
**Economic Weed Thresholds.** There has been a steady progression of research from competitive weed thresholds to economic weed thresholds. Growers are generally more concerned with economic weed thresholds because of their immediate role in production decisions (Oliver 1988). Analogous to competitive weed thresholds, early studies on economic weed thresholds focused on a single time of weed emergence relative to the crop. One of the first economic weed thresholds with a single time of weed emergence was developed by Marra and Carlson (1983). They determined the economic threshold for common cocklebur, tall morningglory (*Ipomea purpurea* (L.) Roth. # PHBPU), smooth pigweed, common ragweed, and Pennsylvania smartweed (*Poygonum pensylvanicum* L. # POLPY) in a soybean crop to be 1.79, 1.53, 2.92, 5.19, and 3.0 weeds per 10 m of soybean row, respectively. Weaver (1991) documented that for soybean grown in Ontario, the economic weed threshold for common cocklebur, velvetleaf, and jimsonweed was 1.4, 2.5, and 0.7 weeds per m². Sattin et al. (1992) reported the economic threshold of velvetleaf in field corn to be from 0.3 to 1.7 plants per m². Bauer and Mortensen (1992) calculated economic thresholds to be 2.6 velvetleaf weeds per 10 m² and 1.5 common sunflower (*Helianthus annuus* L. # HELAN) weeds per 10 m² in soybean.

Much of the economic threshold research completed throughout the world involves cereal crops. Streibig et al. (1989) analyzed data from the literature to determine economic thresholds for various weed species in barley and wheat. Economic threshold densities in wheat were determined for creeping knapweed,
rush skeletonweed (*Chondrilla juncea* L. # CHOJU), wild radish, and annual ryegrass to be 3 to 9 shoots per m², 24 to 60 shoots per m², 18 plants per m², and 76 to 210 plants per m², respectively. The economic threshold for wild radish and annual ryegrass in a barley crop was found to be 31 and 219 plants per m², respectively (Streibig et al. 1989). Zanin et al. (1993) documented numerous economic thresholds for weeds in winter wheat in Europe. For winter wild oats (*Avena sterilis* L. subsp. *ludoviciana* Durieu # AVELU), the economic threshold was between 7 and 12 plants per m², for slender foxtail (*Alopecurus myosuroides* Huds. # ALOMY) and Italian ryegrass (*Lolium multiflorum* Lam. # LOLMU) it varied between 25 and 35 plants per m², while for poverty brome grass (*Bromus sterilis* L. # BROST) the values were just under 40 plants per m².

For catchweed bedstraw (*Galium aparine* L. # GALAP) the threshold was as low as 2 plants per m², while for common vetch (*Vicia sativa* L. # VICSA) it was between 5 and 10 plants per m².

Numerous economic thresholds for weeds in a variety of other agricultural crops have also been reported. The economic threshold for common lambsquarters, greater ammi (*Ammi majus* L. # AMIMA), and wild mustard (*Sinapis arvensis* L. # SINAR) was determined to be 4 to 6 plants per m² in sunflower (Onofri and Tei 1994). Lindquist and Kropff (1996) determined the economic threshold for barnyardgrass in irrigated rice (*Oryza sativa* L.) to be approximately 2.9 plants per m². An economic threshold of 23 quackgrass (*Elytrigia repens* (L.) Nevski. # AGRRE) shoots per m² in canola (*Brassica*
*campestris* L.) has been calculated in Alberta (O’Donovan 1991).

Economic weed thresholds that incorporate multiple times of weed emergence represent the most advanced single weed species thresholds to date. Cardina et al. (1995) documented that the economic threshold for velvetleaf that emerged in a no-tillage corn crop to be 0.13 to 3.13 weeds per m². Velvetleaf that emerged 3 weeks after the corn crop had an economic threshold of 4.7 to 5.8 weeds per m². Two single species economic thresholds with multiple times of weed emergence have been completed in Ontario. Dieleman et al. (1995) recommended that if pigweed emerging with a soybean crop is greater that 0.7 plants per metre of row, as compared to 13.4 plants per m of row emerging 20 growing degree days later, the economic threshold will have been reached. Bosnic and Swanton (1997a) documented that if barnyardgrass emerging with a corn crop is greater that 10.9 plants per m of row, as compared to 42.4 plants per m of row emerging 80 growing degree days later, the economic threshold will have been reached.

Research on single weed species thresholds has progressed from competitive thresholds utilizing a single time of weed emergence, to economic thresholds with multiple times of weed emergence. These threshold studies have become central to the further understanding of crop-weed interactions, and the development of an IWM system. A pre-requisite for improving the weed threshold concept is the prediction of yield losses caused by mixed weed infestations, because traditional one-weed one-crop studies do not reflect the
norm in actual farm situations (Berti and Zanin 1994; Street et al. 1985; Hume 1989; Oliver 1988; Poole and Gill 1987; Sims and Oliver 1990; Stoller et al. 1987; Swinton et al. 1994; Toler et al. 1996; Zanin et al. 1993). Single weed species populations are relatively uncommon in production agriculture. Agricultural fields are normally infested with one or two dominant weed species, and a number of less-abundant or rare species (Hume 1989). Prediction of yield losses from multiple weed species interference, and the subsequent expansion of thresholds to include multiple weed species, is essential for the ongoing development of weed-crop competition models. Limited information is available, however, concerning multi-species threshold values, as well as the effect multiple weed species have on a given crop and each other (Sims and Oliver 1990; Street et al. 1985; Toler et al. 1996).

Multiple Weed Species.

In the majority of papers on multiple weed species interference, the objectives were to either confirm or refute the additivity theory of weed interference, create a viable competitive indexing system, or simply quantify the effects of multiple weed species interference. There are conflicting opinions in the scientific community as to whether additivity exists wholly, partially, or is non-existent. Similar to the additivity debate, concerns have arisen about the validity of many of the competitive weed indices that have been developed over the past 25 years.

Additivity. The inter- and intraspecific competition of weeds growing as a multi-
species are difficult to separate. Some researchers have proposed that the competitive effects of weeds are additive. This theory implies that a crop yield loss incurred by a particular weed species grown individually, can be added to the yield loss incurred by a different species grown individually, resulting in a combined or additive yield loss when the two weeds are present together. Most researchers agree that at high weed densities, where the areas of weed influence overlap, and there is significant inter- and intraspecific competition, the competitive effects are not additive. The discrepancy among researchers is at low weed densities. It is at low weed densities where researchers have argued that the competitive effects of weeds can be fully additive, partially additive, or even non-additive.

One of the first multiple weed species interference studies was completed by Alex (1970) in Regina, Saskatchewan. Field trials investigating cow cockle (Saponaria vaccaria L. # VAAPY) and wild mustard interference in wheat were conducted. Sixty-one cow cockle plants per m² reduced wheat yield by 38.2%, while 39 wild mustard plants per m² caused a 37.4% yield loss. When the same densities of weeds were combined in a multi-species environment, wheat yield loss was 42.4%. He concluded that the effects of both species were not fully additive, because the effects of one species tended to obscure the effects of the other. Haizel and Harper (1973) conducted a multiple weed species interference study in pots in a greenhouse. White mustard (Sinapis alba L. # SINAL), wild oats, and barley were grown at varying densities as a single species, and
together as a multi-species. Twelve white mustard and twelve wild oat plants
grown in monoculture with barley as the principal crop, reduced barley yield by
6.5 and 29.3%, respectively. The yield loss incurred by barley when the weeds
were grown together as a multi-species at the same densities was 31.8%. The
influence of the two weeds together was slightly less than the sum of their
effects acting separately. This experiment demonstrated that effects of weed
species may be partially additive. Conversely, with white mustard as the
principal crop, the effect of barley and wild oat was greater than additive,
suggesting some sort of synergistic effect between the weeds. Street and his
associates (1985) documented the effects of sicklepod (Cassia obtusifolia L. #
CASOB) and mixtures of redroot and smooth pigweed on cotton to be additive at
low densities. For example, 1 pigweed plant per 7.5 m of row reduced cotton
yield by 2.3%, while 1 sicklepod per 7.5 m of row reduced cotton yield by 7.5%.
When 1 pigweed and 1 sicklepod per 7.5 m of row were grown together, seed
cotton yields were reduced by 9.7%. This indicated that at low weed densities
the competitive effect of pigweed and sicklepod was additive, and that
interspecific competition between weeds at these densities was insignificant.
However, when both species were present at the highest weed density (16
plants of each weed per 7.5 m of row), inter- as well as intraspecific competition
occurred and the corresponding multi-species yield loss not additive. Blackshaw
et al. (1987) studied wild mustard and common lambsquarters interference in
spring-sown rapeseed (Brassica napus L.), and discovered evidence both for
and against the theory of additivity. In 1983, rapeseed grain yield was reduced 36 and 25% by 20 plants m$^2$ of wild mustard and common lambsquarters, respectively. When these weed densities were combined, the yield reduction was only slightly greater (39%) than that caused by wild mustard alone. Their 1994 study demonstrated rapeseed yield loss from the multi-species trial to be almost equal to the sum of yield losses incurred by rapeseed from each weed species individually. Sims and Oliver (1990) reported only partial additivity in their study on the effects of sicklepod and johnsongrass on soybean. Soybean yields were reduced 31% by sicklepod at a density of 1 plant per 30 cm of crop row, 14% by johnsongrass at 1 plant per 30 cm of row, and 36% by both weeds at the combined densities. They showed the combined effects of these weeds were less than additive, indicating that the two weeds were interacting by competing for the same resources. Similar to Blackshaw et al. (1987), Toler et al. (1996) observed almost complete additivity in one year, and non-additivity in another. Johnsongrass and smooth pigweed were established in both a mono- and multi-species soybean plot in all possible combinations at densities of 1, 2, 4, and 8 plants per 4.6 m of row. A severe drought in 1986 increased the competitive abilities of the weeds against the soybean crop. Summing the crop yield losses in the monoculture plots exceeded the multi-species yield losses in all circumstances. Ideal growing conditions in 1987 caused yield losses to be lower in all treatments as compared to the dry year. Consequently, almost complete additivity across all combinations and densities was observed. For
example, monospecific densities of johnsongrass and smooth pigweed at 1 and 4 plants per 4.6 m of row, reduced soybean yields by approximately 7 and 17%, respectively. When grown in a multi-species environment at the same densities, the resulting soybean yield loss was 25%. One of the most recent multiple weed species interference studies was conducted by Van Acker et al. (1996) in England. The competitive effects of common chickweed (Stellaria media L. # STEME) and barley on faba bean seed yield (Vicia faba L.) were documented. Weeds were grown at varying densities and combinations in pots. In addition to the competitive interference component of the study, effect of water stress on the competing plants was also investigated. Water stress was imposed by withholding water from designated pots for 11 days, while keeping all other pots moist. With one exception, when both barley and common chickweed were present, the effect on faba bean yield was less than additive. In 1995, when water stress was not imposed, the combined effect of barley and chickweed on faba bean yield was almost completely additive.

Generally additivity at high weed densities does not occur. The question of whether there is additivity at arbitrarily 'low' weed densities has not been addressed clearly. Perhaps the real question concerning additivity at low weed densities, is initially defining what constitutes a 'low' weed density. It is currently unknown where the area of weed influences from different species begin to overlap in a field situation. Van Acker et al. (1996) contend that additivity is dependent on the intensity of interference present. The intensity of interference
is described as a function of the weed species present, their subsequent densities, time of weed emergence relative to the crop, and environmental conditions under which the weeds are growing. Weed densities at which additivity has been documented range from 1 plant per 7.5 m of crop row, and 1 to 4 plants per 4.6 m of crop row by Street et al. (1985) and Toler et al. (1996), respectively. The majority of multiple weed species interference studies that declare additivity to be non-existent, have used weed densities that were quite high, making the non-additive result not unexpected. More multiple weed species research at extremely ‘low’ weed densities is required to determine where the weed areas of influence begin and end in an actual cropping situation.

**Competitive Indexing.** Weeds can be ranked in terms of their competitiveness against a crop. Determining the competitive abilities of weed species in relation to one another is an important component in the development of an IWM cropping system. These weed ‘rankings’ have led to the formation of a competitive index (CI). Growers can use competitive indices to assist their weed control decision making processes. Weeds that are highly competitive against a crop require control measures, while weeds that are less competitive can remain in the field. The use of competitive indices will inevitably lead to a reduction in the amount of herbicides used in agriculture.

Many competitive weed indices have been developed, but there are concerns about the assumptions and methodologies used in deriving them.
Most researchers have sought to develop a competitive index that transforms all weed species into a common unit of weed pressure (Aarts and Visser 1985; Black and Dyson 1993; Coble 1986; Coble and Mortensen 1992; Dew 1972; Lybecker et al. 1991). One approach for constructing competitive weed indices was to survey the expert opinions of weed scientists throughout certain countries or agricultural regions. This has been done by Lybecker et al. (1991) in the United States, and by Black and Dyson (1993) in Australia. Reference weed species were chosen and all remaining weed species were converted to units of these reference species. The dominant approach, however, has been to develop these indices from simple regression coefficients where crop yield is regressed on weed pressure from a single weed species (denominated in weed numbers or biomass) (Swinton et al. 1994). Dew (1972) was one of the first to document an index of competition for estimating crop loss due to weeds. His index of competition was expressed by the ratio between the slope and the intercept of the regression line. Dew (1972) determined that the index of competition indicates the competitive relationship between each crop and weed combination. Barley was found to be the best competitor against wild oat, followed by wheat, with flax being the poorest competitor. Many subsequent competitive indices have used Dew’s index of competition model as a template.

Coble (1986) expanded Dew’s index by making a ratio of the proportional yield loss due to a certain weed relative to the most competitive weed species in the system. The most competitive weed found in Coble’s soybean study was
cocklebur. Cocklebur was then assigned a competitive index value of 10. All remaining weeds in the system were assigned a rating from 0 to 10 according to their impact on crop yield relative to the most competitive reference weed. Coble and Mortensen (1992) went on to construct a Total Competitive Load (TCL) by multiplying the density of each weed species times its competitive index and summing these products to give the total competitive effect in a multiple weed species situation. Aarts and Visser (1985) introduced a weed indexing system for cereals that describes the competitive effect of multiple weed species on the basis of 'Standard Weed Units'. The Standard Weed Units of each species were calculated as the product of the observed weed density and the ratio between 500 and a previously determined economic threshold level for each species. Kroh and Stephenson (1980) developed a relative competitive ability index (RCA) to demonstrate more clearly the intra- and interspecies relationships among species in mixture plots. Competitive indices (CI) were initially calculated by dividing the mean plant weight of species in a mixture, by the mean plant weight of each species in a pure stand. If the CI was greater than one, intraspecific competition was greater than interspecific competition; and if the CI was less than one, interspecific competition dominated. RCA's were determined by summing the CI's of each species, with a greater RCA indicating a more competitive plant (Kroh and Stephenson 1980). Wilson (1986) first proposed the concept of the 'Crop Equivalent' ratios. The competitive ability of a single weed species is expressed as the ratio between weights of individual
weed plants and the weights of weed-free crop plants. The competitive effect of multiple weed species is the sum of the products of the observed densities and the crop equivalent ratio of the individual weed species. Wilson and Wright (1990) later documented that the assumptions inherent in using crop equivalents (based on relative weights of weed and crop plants) were questionable, because with intense competition, weed biomass at harvest failed to replace lost crop biomass, which caused the harvest index to be reduced.

A potential flaw of these approaches is they are either restricted to low, single weed species densities, use single weed species data to develop competitive indices for multiple weed species environments, or are based strictly on plant weight. Furthermore, they do not consider interspecific competition as weed density in a multi-species environment increases. Kroh and Stephenson (1980) investigated the interactions of four weed species in pairs and in mixtures. They discovered that the ranking of these species according to their competitive index, changed, depending on whether the species were grown in pairs or in four-way mixtures. It was concluded that the performance of species in a multi-species environment cannot be predicted from two-species (either weed-weed, or crop-weed) competition experiments. Thus, it is imperative that competitive indices be developed from actual multiple weed species field data.

**Crop-Weed Competition Models.**

In most quantitative studies on crop-weed interference, empirical models have been developed to describe the response of crop yield to one or more
parameters with which weed infestation can be characterized. Competing biological theories support sigmoidal (Zimdahl 1980) and hyperbolic (Cousens 1985a) yield loss functions. The important economic difference is that sigmoidal functions tend to place the control threshold at a higher weed density than the hyperbolic functions (Swinton and King 1994). Cousens (1985a) compared 17 functional forms and found that the rectangular hyperbolic model best explained the data and was most consistent with the underlying biology of crop-weed interference. This model has become widely accepted in the literature for documenting crop yield response to single species weed density (Berti and Zanin 1994; Coble and Mortensen 1992; Lindquist et al. 1996; Norris 1992; Sattin et al. 1992; Stoller et al. 1987; Weaver 1991; Wilson and Wright 1989). Cousens (1985a) stated the original model as

\[ Y = Y_{wf} \left[ 1 - \frac{l w}{100 \left(1 + \frac{w}{A}\right)} \right] \]  

where \( Y_{wf} \), \( l \), and \( A \) are parameters to be estimated from the data, \( Y \) is observed crop yield, and \( w \) is weed density. \( Y_{wf} \) represents weed-free yield, while \( l \) represents percentage loss in crop yield per unit of weed density as density approaches zero, and \( A \) represents the maximum percentage crop yield loss asymptote as weed density approaches infinity. The hyperbolic model has
essentially two linear components: one at low density which is constrained to pass through the origin and which is the result of the additive effect of weeds' intraspecific interference; the other at high density which is constrained at an asymptotic value not exceeding 100% yield loss. At low densities where the area of influence of individual weeds do not overlap, the effect of each weed is additive. As weed density increases, and the areas of weed influence begin to overlap, the interfering effect of each weed on the crop as well as other weeds decreases. The result is a crop yield loss plateau or asymptote.

A different approach to analyze the competitive effects of mixed weed populations has been proposed by Kropff and Spitters (1991). Their model, which is based on the rectangular hyperbola of Cousens (1985a), describes the relationship between crop yield loss and relative weed leaf area instead of weed density as a variable. Lotz et al. (1992) expanded this model to allow for more than one weed species. They reasoned that the use of a relative weed leaf area model would increase the accuracy of prediction because it included the effects of different factors, such as crop vigour, weed density, and relative time of weed emergence. At present, the main disadvantage is that the measurement of leaf area index of crop and weeds does not appear to be fast or reliable in the field (Berti and Zanin 1994).

The rectangular hyperbola in equation 1 can be reformulated as a multivariate regression to account for multiple weed species (Swinton et al. 1994a,b). Using \( w_i \) to denote the density of weed species \( i \) (\( i=1 \) to \( n \), for \( n \) weed
species), this can be written:

\[
Y = Y_{wf} \left[ 1 - \frac{\sum i_i w_i}{100 \left(1 + \sum i_i w_i/A\right)} \right]
\]

(2)

The coefficients estimated have exactly the same interpretation as those in equation 1, except that \( l_i \) values now are percentage yield loss associated with the first weed of species \( i \). The competitive effect of an additional weed species (n) is given by the derivative:

\[
\frac{\partial Y}{\partial w_n} = l_n \left[ \frac{-Y_{wf} A^2}{100 (A + \sum l_i w_i)^2} \right]
\]

(3)

Interspecific weed competition is implicit in equation 3, since the competitive effect of an additional weed of one species depends in part on the density of the other species. Swinton et al. (1994a,b) proposed that the individual coefficients \( l_i \) serve as competitive indices for each weed species. The \( l_i \) coefficients differ from the competitive indices developed by Coble (1985), Black and Dyson (1993), and Lybecker et al. (1991), in that they are estimated from field data including multiple weed species growing together and they do not rely on expert opinion (Swinton and King 1994). The coefficients generated from the Swinton
equation can be converted into the kind of competitive index values associated with Coble and Mortensen’s (1992) competitive load formula by dividing through by the largest \( l_1 \) value (i.e., that of the most competitive weed). This can be illustrated for two weed species by the following equation:

\[
\sum l_i w_i = l_1 w_1 + l_2 w_2 \\
= l_2 \left[ \frac{l_1}{l_2} w_1 + w_2 \right]
\]  
(4)

If weed \( w_2 \) is the most competitive weed in the system (by having the largest \( l_1 \) value), then \( l_2 \) becomes the \( l \) coefficient used in a simple hyperbolic model like that in equation 1. The count of \( w_1 \) weeds is then weighted by a competitive index equal to the ratio \( l_1/l_2 \), putting them in terms of \( w_2 \) weed equivalents. The resulting hyperbolic curve would then have crop yield (\( Y \)) on the vertical axis, and weed density (in terms of most competitive weed equivalents) along the horizontal axis. Both competitive and economic threshold values for a multiple weed species field situation could be generated as a result.

This method for developing weed equivalents, subsequent competitive weed indices, and weed threshold values for actual multiple weed species field data, is essential for the ongoing development of weed-crop competition models, and IWM systems as a whole.

**Soybean, Pigweed, and Barnyardgrass.**

Soybean is an intensively managed row crop that is widely grown in
Ontario. Soybean contains approximately 40% protein and 20% oil on a dry matter basis. Although the oil is used primarily in edible products such as margarine and cooking oil, it is used industrially in such products as high-grade paints and pharmaceuticals (Upfold and Olechowski 1994). The soybean meal that remains after the oil is extracted is almost all used as a high protein feed for livestock. In 1994, Ontario produced 2 068 000 tonnes of soybean worth an estimated value of $ 558 600 000 (approximately $ 270 per tonne) from 759 000 ha of land (Anonymous 1994). Soybean has finally surpassed grain corn as the primary field crop grown in Ontario on a hectare basis.

Herbicides continue to be used as the primary means of weed control in soybean production (Upfold and Olechowski 1994). However, weeds still cause major yield losses in soybean. In Ontario, between 1985 and 1989, weeds reduced soybean yields by 10%, resulting in a loss of $ 31 800 000 (Swanton et al. 1993). Weeds can decrease soybean yield, increase harvest losses by interfering with harvesting operations, and lower seed quality by contaminating the soybean crop with residue and weed seeds (Anderson and McWhorter 1976). Soybean yield is affected by weeds as a result of competition between the crop and associated weeds for growth-limiting resources, such as light, water, and nutrients (Kropff and Lotz 1992). A comprehensive review of weed interference in soybean has been provided by Stoller et al. (1987).

Pigweed and barnyardgrass commonly occur in many temperate-zone cropping areas throughout the world (Maun and Barrett 1986; Siriwardana and
They are also major weed escapes in soybean fields throughout Ontario. Pigweed and barnyardgrass ranked fourth and tenth, respectively, in terms of the most abundant weeds of field crops grown in southwestern Ontario (Frick and Thomas 1992). Pigweed was found at a mean density of 2.1 plants per m² in approximately 41% of surveyed fields, while barnyardgrass was found at a mean density of 0.6 plants per m² in 16% of surveyed fields.

Pigweed interference has been studied in a variety of field crops: corn (Frantik 1994; Knezevic et al. 1995; Moolani et al. 1964), potato (Vangessel and Renner 1990), sugarbeet (Evans and Dexter 1982; Schweizer and Lauridson 1985; Senesac and Minotti 1979), cotton (Buchanan et al. 1980a,b; Buchanan and Burns 1971; Street et al. 1985), tomato (Qasem 1992), and soybean (Dieleman et al. 1995a; Legere and Schreiber 1989; Marra and Carlson 1983; Monks and Oliver 1988; Moolani et al. 1964; Orwick and Schreiber 1979; Shurtleff and Coble 1985; Toler et al. 1996; Van Acker et al. 1993a).

There are three main species of pigweed found in Ontario: redroot, Powell amaranth, and smooth pigweed. These species of pigweed are annuals and each possess the C₄ pathway of photosynthesis. They are seldom found in closed or shaded communities. Plants of all three species have an indeterminate growth habit and are able to germinate and emerge throughout the growing season given adequate moisture (Weaver and McWilliams 1980). All three species are self-compatible and are chiefly self-pollinated. Plants of all
species can range in height from 0.1 to 2.0 m. A single, vigorous plant of Powell amaranth, redroot, or smooth pigweed may produce as many as 100,000 fruits with one seed per fruit (Weaver and McWilliams 1980).

Successful above-ground competition depends primarily on pigweed's ability to overshadow the crop (or other weed species) plant and intercept a greater share of incident solar radiation (Stoller et al. 1987). Legere and Schreiber (1989) documented that pigweed leaf area was concentrated in the upper strata of a soybean canopy resulting in reduced light availability to the soybean leaves lower in the canopy. Kroh and Stephenson (1980) determined the competitive ability of four weed species from highest to lowest to be, redroot pigweed, common lambsquarters, green foxtail, and witchgrass (Panicum capillare L. # PANCA). In a comparison of common cocklebur, common lambsquarters, common ragweed, and sicklepod, redroot pigweed attained the highest plant height in soybean, and was second only to common cocklebur with respect to competitive ability (Shurtleff and Coble 1985). They proposed that the competitive ability of pigweed be attributed to its height difference relative to that of soybean. Toler et al. (1996) determined the competitive ability of smooth pigweed to be greater than that of johnsongrass in soybean. They proposed that the superior competitive ability of smooth pigweed is most likely related to light exclusion associated with greater leaf area and total biomass production by smooth pigweed compared to johnsongrass. The study by Toler et al. (1996) supports the contention by Muzik (1970) that competitive effects are generally
greater within than between Monocotyledoneae and Dicotyledoneae.

Similar to pigweed, barnyardgrass interference has been studied in a variety of field crops: corn (Bosnic and Swanton 1997a,b; Spitters et al. 1989), sugarbeets (Norris 1992), potatoes (Vangessel and Renner 1990), rice (Bhowmik and Reddy 1988; Chisaka 1977; Smith 1968), cotton, (Keeley and Thullen 1991), and soybean (Maun 1977; Vail and Oliver 1993; Van Acker et al. 1993).

Barnyardgrass is a major annual grass weed problem throughout the world. The success of this weed may be attributed to the production of large numbers of small, easily dispersed seeds per plant, possession of seed dormancy, rapid development and ability to flower under a wide range of photoperiods, and relative resistance of mature plants to herbicides (Maun and Barrett 1986). Barnyardgrass is a C₄ plant. Analogous to other C₄ plants, barnyardgrass prefers warm regions, where there is an abundance of moisture for plant growth and seed dispersal. Barnyardgrass can be found growing on a wide variety of soil types and textures. Soils with relatively high water holding capacity and high fertility provide an ideal substrate (Maun and Barrett 1986). In southwestern Ontario, maximum emergence of barnyardgrass seedlings occurs in the beginning of June and continues intermittently throughout the summer. Late summer flushes can still produce seed, because the plant sacrifices vegetative growth for quick flowering (Holm et al. 1977). The mating system of barnyardgrass involves a high degree of self-fertilization with occasional
outcrossing mediated by wind. Barnyardgrass is considered the world's principal weed of rice (Holm et al. 1977; Maun and Barrett 1986). It has similar ecological preferences to rice, and young plants look very similar (Yabuno 1966). Heavy infestations may remove 60 to 80% of the nitrogen from the soil (Holm et al. 1977), as well as considerable amounts of other macronutrients at the expense of crop plants, thus reducing their yields, especially when these elements are in short supply (Vengris 1953). Barnyardgrass plants are highly susceptible to shading. The number of tillers and panicles per plant are always greater in full sunlight than in heavy shade. It does not represent a serious threat to crops that are tall, vigorous, and are established before the weed.

There have been few studies documenting the effects pigweed and barnyardgrass have on each other, as well as on a crop in an actual cropping situation. Roush and Radosevich (1985) studied the competitive relationships between redroot pigweed, common lambsquarters, barnyardgrass, and black nightshade (Solanum nigrum L. # SOLNI) in a non-crop field environment. Barnyardgrass was found to be the superior competitor when grown in mixture with the other three species. Pigweed was suppressed when grown in combination with barnyardgrass, but was superior to the other weeds. Sirwardana and Zimdahl (1984) documented the growth and competition of pigweed and barnyardgrass in styrofoam pots in a greenhouse environment. They concluded that barnyardgrass was more competitive than pigweed and that the intraspecific competition of barnyardgrass was greater than interspecific
competition from redroot pigweed. Vangessel and Renner (1990) conducted both replacement series greenhouse experiments and field experiments on redroot pigweed and barnyardgrass interference in potatoes. In the greenhouse experiments, barnyardgrass was determined to be more competitive than redroot pigweed as measured by Kroh and Stephenson's relative competitive ability function. However, redroot pigweed reduced tuber yield more than barnyardgrass in one year of field research (Vangessel and Renner 1990).

Project Objectives.

There is still much uncertainty regarding the competitive abilities of pigweed and barnyardgrass. They are two of the most common weeds found in Ontario's agricultural fields. Analogous to the pigweed and barnyardgrass competitive ability discrepancy, viable competitive weed indices have yet to be established. Established competitive weed indices are the foundation for further modelling research. Weed thresholds need to be expanded to include multiple weed species. This will inevitably lead to greater efficiency of herbicide use, and a reduction in the amount of herbicides applied to the environment. Therefore, a multiple weed species interference study involving pigweed and barnyardgrass in soybean would be most appropriate for the development of an IWM system for today's agricultural producer. The objectives of this study were to determine: 1) the influence of time of emergence and density of single and multi-species pigweed and barnyardgrass populations on soybean yield, and 2)
the competitive abilities of pigweed and barnyardgrass across environments.

*Abstract.* Field experiments were conducted to determine the influence of time of emergence and density of single and multi-species populations of pigweed and barnyardgrass on soybean yield and competitive abilities of pigweed and barnyardgrass. Pigweed and barnyardgrass were established at selected densities within 12.5 cm on either side of the soybean row. Pigweed and barnyardgrass seeds were sown concurrently with soybean and at the cotyledon stage of soybean growth. Time and density of pigweed and barnyardgrass seedling emergence relative to soybean influenced the magnitude of soybean yield loss. Maximum soybean yield loss ranged from 32 to 99%, depending upon time of emergence relative to soybean. Pigweed was more competitive than barnyardgrass across all locations, years, and time of weed emergence. When pigweed was assigned a competitive index of 1.0 on a scale from 0 to 1, the competitive ability of barnyardgrass ranged from 0.075 to 0.40 of pigweed, depending upon location and time of emergence. Competitive indexing studies must be conducted in combination with a crop under differing environmental conditions. *Nomenclature:* Powell amaranth, *Amaranthus powellii* S. Wats. #
AMAPO; redroot pigweed, *Amaranthus retroflexus* L. # AMARE; barnyardgrass, *Echinochloa crus-galli* (L.) Beauv. # ECHCG; soybean, *Glycine max* (L.) Merr. 'Pride KG 60' and 'Pioneer 9302'.

**Key Words:** Integrated weed management, multi-species interference, multiple weed species, mixed weed populations, threshold, time of emergence, weed density, yield loss, competitive index.
INTRODUCTION

Weed management is essential for a profitable agricultural system. In North America, herbicides have been used as one of the primary tools for managing weed populations during the latter half of the twentieth century. Extensive herbicide use was one of the main reasons that an abundant and economical food supply has been maintained in agriculturally developed nations (Coble 1994; Kropff and Lotz 1992). However, increasing herbicide resistance in certain weeds, rising costs, and widespread concern about environmental impacts have resulted in greater pressure on producers to reduce herbicide use (Kropff and Lotz 1992; Swanton and Murphy 1996). Integrated weed management (IWM) strategies are being developed for Ontario agriculture to increase the efficiency of herbicide use and to reduce the amount of herbicides applied into the environment. IWM incorporates crop breeding, fertilization, rotation, chemical weed control, mechanical weed control, competition, successional management, and soil management into a method of reducing weed interference while maintaining acceptable crop yields (Swanton and Murphy 1996). Weed thresholds are one component of an IWM system that can assist in achieving this goal.

Weed thresholds help agricultural producers determine the necessity and

1Abbreviations: IWM, integrated weed management; OCHU, Ontario Corn Heat Units; RSS, residual sum of squares; SS, sums of squares.
timing of herbicides (Knezevic et al. 1994; Swanton and Weise 1991). The vast majority of weed threshold research has been conducted with a single weed species in a single crop. This has been done empirically in soybean (Bauer and Mortensen 1992; Dieleman et al. 1995; Vail and Oliver 1993; Weaver 1991), dry bean (Chikoye et al. 1995), corn (Bosnić and Swanton 1997b; Cardina et al. 1995; Knezevic et al. 1994; Lindquist et al. 1996), sugarbeets (Kropff 1988; Norris 1992; Schweizer and Lauridson 1985), tomato (Bhowmik and Reddy 1988; Weaver et al. 1987) and other field crops. Research on single weed species thresholds have included competitive thresholds utilizing a single time of weed emergence, and economic thresholds incorporating multiple times of weed emergence (Bosnić and Swanton 1997a; Dieleman et al. 1996). These threshold studies have become central to the understanding of crop-weed interactions and the development of an IWM system. A pre-requisite for the utilization of weed thresholds is the ability to predict yield losses caused by multiple weed species populations, because traditional studies using a single weed and crop species do not reflect the norm in growers' fields (Berti and Zanin 1994; Hume 1989; Oliver 1988; Sims and Oliver 1990; Stoller et al. 1987; Street et al. 1985; Swinton et al. 1994a; Toler et al. 1996; Zanin et al. 1993).

Studies have been reported on multiple weed species interference in wheat (Alex 1970), barley (Haizel and Harper 1973), cotton (Street et al. 1985), rapeseed (Blackshaw et al. 1987), potato (Vangessel and Renner 1990) and faba bean (Van Acker 1996). These studies demonstrated that the effect of a
mixture of weeds on a crop cannot be predicted from the effects of the weed species acting separately. Haizel and Harper (1973) concluded that mixtures of weeds may produce less effect than the sum of their independent actions. This is particularly true at high weed densities, because the effects of one weed species tended to obscure the effects of the other weed species (Alex 1970; Blackshaw et al. 1987; Haizel and Harper 1973; Street et al. 1985; Van Acker 1996).

Only two multiple weed species studies have been conducted in soybean. Sims et al. (1990) found soybean yields in Arkansas to be reduced more by sicklepod than seedling johnsongrass (Sorghum halepense L.). They concluded that soybean yield reduction from a multi-species population of both weeds was no greater than that of sicklepod alone. More recently, Toler et al. (1996) determined that multi-species populations of smooth pigweed (Amaranthus hybridus L.) and seedling johnsongrass were more competitive with soybean than johnsongrass alone. However, they detected no differences in competitiveness between the multi-species populations and smooth pigweed grown alone. However, none of these studies incorporated time of weed emergence relative to the crop within their experimental design.

The time of weed emergence relative to the crop has been shown to be critical in determining the outcome of weed competition (Bosnić and Swanton 1997b; Chikoye et al. 1995; Dieleman et al. 1995; Knezevic et al. 1994; Kropff 1988; O'Donovan et al. 1985). Dieleman et al. (1995) demonstrated that a
pigweed density of 2 plants m\(^{-1}\) emerging at the same time as soybean resulted in 12.3% soybean yield loss compared to 0% for pigweed emergence at the second node growth stage of soybean. Thirty barnyardgrass plants m\(^{-1}\) emerging at the 3-leaf corn stage resulted in 14% yield loss compared to 4% for emergence at the 7-leaf corn stage (Bosnic and Swanton 1997b). The inclusion of time of weed emergence relative to the crop in a multiple weed species environment will improve upon prediction of crop yield loss. In addition, the question of whether competitive indices for multiple weed species populations will change depending upon the time of weed emergence needs to be addressed.

Redroot pigweed (*Amaranthus retroflexus* L.), Powell amaranth (*Amaranthus powellii* L.) and barnyardgrass (*Echinochloa crus-galli* L.) are common weed escapes in soybean in Ontario. Barnyardgrass and pigweed can reduce soybean yield up to 50% and 45%, respectively, when grown separately depending upon density and time of emergence (Dieleman et al. 1995; Vail and Oliver 1993). There remains uncertainty, however, as to the relative competitive abilities and threshold levels of these weeds when grown with soybean. Therefore, a multi-species interference study involving pigweed and barnyardgrass in soybean was conducted to determine: 1) influence of time of emergence and density of single and multi-species pigweed and barnyardgrass populations on soybean yield, and 2) competitive abilities of pigweed and barnyardgrass across environments.
METHODS AND MATERIALS

Experimental Locations. Field studies were established at the research stations at Woodstock and Harrow in Woodstock and Harrow, Ontario, in 1995 and 1996. The soil types at Woodstock were a Guelph sandy loam (Grey Brown Podzolic; 53% sand, 34% silt, 13% clay, 3.3% organic matter, pH 7.5) and a Guelph silt loam (Grey Brown Podzolic; 38.1% sand, 45.8% silt, 16.1% clay, 4.3% organic matter, pH 6.7) in 1995 and 1996, respectively. The soil in both years at Harrow was a Fox sandy loam (Hapludalf subgroup; 82.5% sand, 5.0% silt, 12.5% clay, 2.3% organic matter, pH 6.6).

Seasonal temperatures and rainfall varied between locations and years (Table 1). Soil moisture at planting was sufficient for uniform germination and emergence of crop and weeds at both locations. However, at Woodstock in 1996, barnyardgrass emergence at the second timing was poor. Optimal growing conditions occurred at Woodstock in both years and at Harrow in 1995. At Harrow in 1996, rainfall was below the 30-year average during May through August.

Experimental Procedures. At Woodstock, primary tillage consisted of spring chisel plowing followed by cultivation. Tillage practices at Harrow consisted of spring moldboard plowing of a rye cover crop, followed by discing and cultivation. Recommended cultural practices for soybean production were used (Anonymous 1994). 'Pride KG 60' and 'Pioneer 9302' (2775 and 3175 OCHU'),
respectively) soybean cultivars were planted at 90 kg ha\(^{-1}\) in 50 cm wide rows on May 18 and 28 at Woodstock, and May 18 and 22 at Harrow in 1995 and 1996, respectively. 'Pride KG 60' and 'Pioneer 9302' were considered to be mid- and late season cultivars, respectively, for Ontario conditions.

Barnyardgrass seed and mixtures of redroot pigweed and Powell amaranth (hereafter referred to as pigweed) seed were collected at Woodstock and Harrow in 1994 and stored at 5°C. In the spring of each year, weed seeds were placed at room temperature for two weeks. Prior to sowing, weed seeds were soaked in water for 48 h and then air dried. Immediately after soybean planting and at the cotyledon growth stage of soybean (VC), pigweed and barnyardgrass seed were planted in a 25 cm band over the soybean row. Dates of weed sowing were selected so that emergence times coincided with specific soybean growth stages within the time frame of the critical weed-free period (Van Acker et al. 1993). Treatments consisted of a soybean crop with varying densities of pigweed as a single species, barnyardgrass as a single species, and a multi-species population of pigweed and barnyardgrass. The trial at Woodstock included two sowing dates. At Harrow weeds were seeded concurrently with the soybean crop.

Pigweed seedlings emerged at Woodstock at the same time as the soybean crop (VE) and at the second node growth stage of soybean (V2), approximately 10 to 12 d (81 to 109 degree days, base temperature = 10°C)

\(^2\)Soybean growth stages as described by Fehr and Caviness (1977).
after soybean emergence. Barnyardgrass emerged at Woodstock with the crop (VE), and at the third node growth stage of soybean (V3), approximately 17 to 18 d (130 to 169 degree days base temperature = 9.7°C) after soybean emergence. Base temperatures for pigweed and barnyardgrass originated from Wiese and Binning (1987). Crop and weed emergence occurred simultaneously (VE) at Harrow. Emergence times were based on approximately 50% weed and crop emergence.

Pigweed and barnyardgrass seedlings emerging within the single weed species treatments were hand thinned to obtain densities of 0, 0.5, 1, 2, 4, and 0, 10, 30, 60, 100 plants m\(^{-1}\) of soybean row, respectively, at the first emergence date (VE) in both years and locations. Pigweed and barnyardgrass seedlings that emerged in the multi-species treatments at the first (VE) and second emergence dates (V2 and V3), were hand thinned to density combinations of 0.5/10, 1/30, 2/60, and 4/100 plants m\(^{-1}\) of row, respectively, in both years and locations. Weeds grown separately that emerged at the V2 and V3 stage of soybean were maintained at densities of 0.5 and 10, 2 and 60, and 4 and 100 pigweed and barnyardgrass plants m\(^{-1}\) of soybean row at Woodstock only. An additional pigweed density of 8 plants m\(^{-1}\) of row in the single species pigweed treatment was planted to coincide with the 1st emergence date (VE) at Woodstock and Harrow in 1996. To define the maximum soybean yield loss due to high pigweed and barnyardgrass densities, an unthinned high density treatment plot of pigweed, barnyardgrass, and a multi-species mixture of both
weeds emerging with the crop (VE), and at the second to third node growth stage of soybean (V2 to V3) was included at Woodstock.

The interrow space (outside the 25 cm band) was kept weed-free by hand hoeing. Broadleaf weeds at Woodstock were controlled in the single species barnyardgrass treatments with bentazon [3-(1-methylethyl)-(1H)-2,1,3-benzothiadiazin-4(3H)-one 2,2-dioxide] POST at 1.0 kg ai ha\(^{-1}\) in 200 L ha\(^{-1}\) water at 180 kPa using a hand held CO\(_2\) sprayer.

The experimental design was a randomized complete block with four replications. Plots were 4 rows 2 m wide by 8 m in length with weeds established in the middle two rows. Soybeans were harvested manually at physiological maturity (R8) on September 25, 1995, and October 10, 1996, and October 11, 1995, and October 12, 1996 at Woodstock and Harrow, respectively. The crop was hand-clipped from a 4 m section of the centre two rows in each plot, hand-fed into a mechanical thresher\(^3\), and dried at 30°C to a constant weight. Final soybean seed yield was adjusted to 14% moisture.

**Statistical Analysis.** The relationship of soybean yield to various combinations of pigweed and barnyardgrass densities was analyzed by fitting the data sets separately for each location, year, and time of emergence, to a multivariate form of the Cousens' (1985) hyperbolic crop yield model. Swinton et al. (1994a) expanded the original equation to account for multiple weed species:

\(^3\)Hege 125 plot combine, Hans-Ulrich Hege, Domane Hohebuch D7112, Waldenburg, Germany.
\[
Y = Y_{wfr} \left[ 1 - \left\{ \sum w_i / 100(1 + \sum w_i / A) \right\} \right]
\]  

(5)

where \(Y\) is the observed yield (kg ha\(^{-1}\)), \(Y_{wfr}\), \(l_i\), and \(A\) are model parameters to be estimated from the data, and \(w_i\) denotes the density (plants m\(^{-1}\) of row) of each weed species \(i\) (\(i = 1\) to \(n\), for \(n\) weed species). Parameter \(Y_{wfr}\) represents weed-free yield, \(l_i\) represents percentage crop yield loss associated with the first weed of species \(i\) per unit weed density, as weed density of the first weed species approaches zero, and \(A\) represents the maximum percentage crop yield loss as weed density of the first weed species approaches infinity. The model parameter estimates were determined from equation 5 for each location, year, and time of weed emergence using nonlinear regression techniques (SAS 1990).

A test for lack of fit of equation 5 was performed by partitioning the nonlinear sums of squares (RSS)\(^1\) into the error for lack of fit and pure experimental error (Draper and Smith 1981). If an F-test value for lack of fit sums of squares (SS)\(^1\) was not significant at the 5% level, the nonlinear model was deemed appropriate for that location, year, and time of weed emergence (Dieleman et al. 1995; Draper and Smith 1981).

Parameter estimates of equation 5 for each location, year, and time of emergence were compared using the method proposed by Chism et al. (1992). This was accomplished by using estimated variables for each location, year, and time of weed emergence, to calculate differences between the model parameter ("S" parameters). For example, in comparing the regression fit for one location
between two years, \( S_0 = (Y_{wf} \text{ for } 1995) - (Y_{wf} \text{ for } 1996), S_1 = (I_1 \text{ for } 1995) - (I_1 \text{ for } 1996), S_2 = (I_2 \text{ for } 1995) - (I_2 \text{ for } 1996), S_3 = (A \text{ for } 1995) - (A \text{ for } 1996). \)

Significant differences exist (\( P< 0.05 \)) when the upper and lower confidence intervals for the "\( S \)" parameters do not contain zero (Chism et al. 1992).

Swinton et al. (1994b) proposed that the initial slope parameters (\( I_1 \) and \( I_2 \) for the two weed species in this study) could be used to calculate competitive indices for each weed species. This is accomplished by dividing the lowest \( I \) value (e.g. \( I_2 \)) by the largest \( I \) value (e.g. \( I_1 \)), for each location, year, and time of emergence. The density of the weed with the lowest \( I \) value is then multiplied by the ratio \( I_2 / I_1 \), thus converting its numbers to the equivalent density of the weed with the highest \( I \) value. The total competitive load (Coble and Mortensen 1992) would then be the sum of density equivalents of both species. The multiple weed species field data was plotted:

\[
Y_L = lw / \left[ 1 + (lw / A) \right]
\]

(6)

where \( Y_L \) is percentage crop yield loss, \( I \) is the largest \( I \) value from the most competitive weed species from equation 5, and \( w \) is the total density equivalents (Swinton et al. 1994a). Analyses were performed separately for each location, year, and time of weed emergence.
RESULTS AND DISCUSSION

Time and density of multi-species seedling emergence relative to soybean influenced the magnitude of soybean yield loss. Soybean seed yield varied with location, year, time of emergence and pigweed and barnyardgrass density. Observed weed-free yields varied from 1986 to 4016 kg ha⁻¹ (Table 2). A satisfactory fit to equation 5 was obtained for all soybean seed yield data sets (based on the test for lack of fit), except for the second weed emergence timing at Woodstock in 1996. This lack of fit may be a result of a restricted range of barnyardgrass densities for the second emergence timing at Woodstock in 1996. Estimated weed-free yield (Yₜ) for each location and year did not differ from observed weed-free yields but did vary among locations and years. For example, the estimated Yₜ (3742 kg ha⁻¹) at Woodstock in 1995 was different (P< 0.05) than the estimated Yₜ (1759 kg ha⁻¹) at Harrow in 1996 (Table 3). These differences in estimated yields between locations may be the result of differing crop cultivars, soil types, and environmental conditions (Bosnić and Swanton 1997b; Dieleman et al. 1995; Stoller et al. 1987; Weaver 1991).

The I parameter for pigweed was greater than the I parameter for barnyardgrass across all locations, years, and times of weed emergence (Table 2). Estimates of yield loss at low pigweed densities, parameter I₁, ranged from 5.6 to 20.1% for pigweed emerging with the crop. Pigweed emerging at the V2 stage of soybean at low weed densities had an estimated I₁ parameter of 3.4%.
Estimates of yield loss at low barnyardgrass densities ranged from 0.95 to 4.8%, for barnyardgrass emerging with the crop, and 0.7% when emerging at the V3 stage of soybean.

The relative competitiveness of each weed species, characterized by the range in I values was influenced by environmental conditions. For example, under conditions of adequate rainfall (see Table 1) at Woodstock in 1995, pigweed and barnyardgrass that emerged at the V2 and V3 stage of soybean growth had I values of 3.4 and 0.7%, respectively (Table 2). At Harrow in 1996 under dry conditions, the I values for pigweed and barnyardgrass emerging with the soybean were 20.1 and 1.5%, respectively. Pigweed was consistently more competitive than barnyardgrass across these contrasting environments. This observation indicates that environmental conditions and time of weed emergence play a significant role in determining the degree of intra and interspecific interference.

The asymptotic yield loss at high pigweed and barnyardgrass densities, parameter A, ranged from 32% at Woodstock in 1995 when both weeds emerged at the V2 to V3 stage of soybean, to 99% for weeds emerging concurrently with soybean at Harrow in 1996 under dry conditions (Table 2; Figure 1).

I and A parameter estimates were not consistent across location, year, and time of weed emergence based on estimated 'dummy' variable analysis (Table 3). For example, the estimated I, value for pigweed emerging with the
soybean crop at Woodstock in 1996 differed (P< 0.05) from the I₁ value at Harrow in 1996. However, the estimated I₂ values for barnyardgrass seedlings emerging with the soybean at Woodstock and Harrow in 1996 did not differ significantly. Analogous to the initial slope parameters, environmental conditions and time of weed emergence contributed to variation in the asymptotic parameter.

**Pigweed was more competitive than barnyardgrass.** Pigweed was assigned a competitive index of 1.0 on a scale from 0 to 1.0. Competitive indices for barnyardgrass, calculated as I₂ / I₁, ranged from 0.075 to 0.4 (Table 4). The fit of the multi-species data to equation 6 in terms of pigweed equivalents is shown in Figure 1. Weed threshold values in terms of pigweed equivalents were calculated at the 2.5, 5, and 10% soybean yield loss levels (Table 5). At a 5% yield loss level at Harrow and Woodstock in 1996, for weeds emerging with soybean, pigweed equivalent densities varied from 0.26 to 0.98 plants m⁻¹ of row, respectively (Table 5). At Woodstock in 1995 and 1996, the pigweed equivalent density required to cause a 5% soybean yield loss varied from 0.44 to 0.98 plants m⁻¹ of row for weeds emerging concurrently with soybean, respectively. Under dry conditions at Harrow in 1996, the number of pigweed equivalents required to cause a 5% soybean yield loss for weeds emerging with the soybean crop was 0.26 plants m⁻¹ of row. Weeds emerging at the V2 to V3 stage of soybean growth were less competitive than earlier emerging weeds at Woodstock in 1995 with a threshold at the 5% soybean yield loss level of 1.75
pigweed equivalents m⁻¹ of row compared to 0.44 pigweed equivalents m⁻¹ of row. Pigweed equivalent densities can consist of various combinations of actual pigweed and barnyardgrass densities. For example, at Woodstock in 1995 (emergence timing 2), using the conversion factor of 0.21 (see Table 4), the threshold level of 1.75 pigweed equivalents at the 5% soybean yield loss level could consist of 1.75 pigweed plants, 1.0 pigweed plus 3.6 barnyardgrass plants, 8.3 barnyardgrass plants alone, or any combination of the two weed species.

In this study pigweed was consistently more competitive than barnyardgrass across all locations, years, and times of weed emergence. Our results are in contrast to previously published work (Roush and Radosevich 1985; Sirwardana and Zimdahl 1984; Vangessel and Renner 1990). In these studies, barnyardgrass was shown to be a stronger competitor than pigweed using weed biomass as an indicator of weed competitiveness in greenhouse pot experiments (Sirwardana and Zimdahl 1984; Vangessel and Renner 1990) and in non-crop field environments (Roush and Radosevich 1985). However, a competitive index based on crop yield losses from actual multiple weed species field data will reflect the relative competitive ability of a weed more accurately than biomass (Wilson and Wright 1990). In our study, we evaluated the competitive abilities of pigweed and barnyardgrass under two contrasting environments. Woodstock and Harrow represent two distinct soybean growing regions in Ontario. Streibig et al. (1989) stated that competitive indexing studies must be conducted over a wide range of environmental conditions if they are to
have any practical application.

**Implications for Management.** Results of this research may overestimate the impact of pigweed and barnyardgrass density, as well as time of emergence on soybean yield loss. Research in Ontario and elsewhere has demonstrated that weeds escaping a soil applied herbicide may have less competitive ability than weeds growing in untreated areas (Adcock and Banks 1991; Weaver 1991). In fields where pigweed and barnyardgrass have escaped a soil applied herbicide, soybean yield losses may be lower than the values reported in this study.

Weed threshold information, expanded to include multiple weed species, should be used as a tool in aiding farm weed management decisions. Analogous to weed threshold information, competitive indices can be used by growers to assist their weed control decision making processes. Based on the results from our study, pigweed should be given a higher priority for control than barnyardgrass. The decision to leave weeds in the field ultimately remains the grower’s decision, however, competitive indices can provide additional information to the grower which may lead to a reduction in the amount of herbicides used in Ontario agriculture.

In summary, the results of our study confirm that time of weed emergence relative to the crop was crucial in determining the magnitude of crop yield loss. Pigweed was found to be more competitive than barnyardgrass in soybean across environments. Coble (1986) created a competitive index for 76 weed species in soybean, and found pigweed to be more competitive than
barnyardgrass, but less than cocklebur, the most competitive weed in soybean in North Carolina. Consequently, pigweed should be given a higher priority for control than barnyardgrass in soybean. Our results support Muzik (1970), Sims and Oliver (1990) and Toler et al. (1996) who found the competitive effects to be greater within Dicotyledoneae and Monocotyledoneae than between them. Berti and Zanin (1994) found dicotyledonous weeds more competitive than monocotyledonous weeds at low weed densities. It is at low weed densities where threshold values are most useful to growers. Competitive index values for multiple weed species must be calculated from field experiments in which weeds are grown in combination with the crop under differing environmental conditions. Future multi-species competitive indexing studies should be conducted using weeds within the same sub-phylum (e.g. Dicotyledoneae and Monocotyledoneae). A competitive index ranking multi-species mixtures of broadleaf weeds and grass weeds separately would improve our understanding of crop-weed and weed-weed interactions.
Table 1. Monthly rainfall (mm), mean daily temperature (°C), and the long-term (30 yr) average for Woodstock and Harrow from May until September in 1995 and 1996.

<table>
<thead>
<tr>
<th>Location</th>
<th>Month</th>
<th>1995</th>
<th>1996</th>
<th>Average</th>
<th>1995</th>
<th>1996</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woodstock</td>
<td>May</td>
<td>96</td>
<td>137</td>
<td>63</td>
<td>13</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>June</td>
<td>78</td>
<td>103</td>
<td>82</td>
<td>20</td>
<td>19</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>July</td>
<td>51</td>
<td>107</td>
<td>80</td>
<td>21</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>August</td>
<td>138</td>
<td>99</td>
<td>87</td>
<td>21</td>
<td>20</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>September</td>
<td>27</td>
<td>253</td>
<td>78</td>
<td>14</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>390</td>
<td>699</td>
<td>390</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Harrow</td>
<td>May</td>
<td>78</td>
<td>25</td>
<td>80</td>
<td>15</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>June</td>
<td>48</td>
<td>80</td>
<td>81</td>
<td>21</td>
<td>21</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>July</td>
<td>104</td>
<td>56</td>
<td>92</td>
<td>24</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>August</td>
<td>108</td>
<td>23</td>
<td>82</td>
<td>24</td>
<td>22</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>September</td>
<td>20</td>
<td>148</td>
<td>85</td>
<td>16</td>
<td>18</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>358</td>
<td>332</td>
<td>420</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
Table 2. Observed weed-free soybean seed yields and parameter estimates (±S.E.) from equation 5.

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Timing</th>
<th>weed-free yield</th>
<th>Oberved mean</th>
<th>Parameter estimates$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>kg ha$^{-1}$</td>
<td>kg ha$^{-1}$</td>
<td>%</td>
</tr>
<tr>
<td>Woodstock</td>
<td>1995</td>
<td>1</td>
<td>3652 (183)</td>
<td>3742 (115)</td>
<td>12.3 (3.7)</td>
</tr>
<tr>
<td>Woodstock</td>
<td>1995</td>
<td>2</td>
<td>3652 (183)</td>
<td>3734 (112)</td>
<td>3.4 (2.3)</td>
</tr>
<tr>
<td>Woodstock</td>
<td>1996</td>
<td>1</td>
<td>3149 (229)</td>
<td>3294 (143)</td>
<td>5.6 (3.8)</td>
</tr>
<tr>
<td>Woodstock</td>
<td>1996</td>
<td>2</td>
<td>3149 (229)</td>
<td>(lack of fit)</td>
<td></td>
</tr>
<tr>
<td>Harrow</td>
<td>1995</td>
<td>1</td>
<td>4016 (86)</td>
<td>3987 (124)</td>
<td>12.2 (3.1)</td>
</tr>
<tr>
<td>Harrow</td>
<td>1996</td>
<td>1</td>
<td>1986 (257)</td>
<td>1759 (110)</td>
<td>20.1 (5.5)</td>
</tr>
</tbody>
</table>

$^a$ $Y_{wf}$ represents predicted weed-free yield, $I_1$ is the percent yield loss caused by pigweed as density approaches zero, $I_2$ is the percent yield loss caused by barnyardgrass as density approaches zero, and $A$ represents the asymptotic yield loss at high weed densities of both species.

$^b$ Timing indicates weed emergence relative to soybean emergence: (1) at soybean emergence (VE); (2) at the V2 to V3 stage of soybean.
Table 3. Pairwise comparisons of estimated parameters from equation 5 between each location, year, and time of emergence.

<table>
<thead>
<tr>
<th>Location, year, and timing</th>
<th>Parameter Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Y_{wf}$</td>
</tr>
<tr>
<td>Woodstock 1995 (1) vs</td>
<td></td>
</tr>
<tr>
<td>Woodstock 1995 (2)</td>
<td>NS</td>
</tr>
<tr>
<td>Woodstock 1996 (1)</td>
<td>*</td>
</tr>
<tr>
<td>Harrow 1995 (1)</td>
<td>NS</td>
</tr>
<tr>
<td>Harrow 1996 (1)</td>
<td>*</td>
</tr>
<tr>
<td>Woodstock 1996 (1) vs</td>
<td></td>
</tr>
<tr>
<td>Woodstock 1995 (2)</td>
<td>*</td>
</tr>
<tr>
<td>Harrow 1995 (1)</td>
<td>*</td>
</tr>
<tr>
<td>Harrow 1996 (1)</td>
<td>*</td>
</tr>
<tr>
<td>Harrow 1995 (1) vs</td>
<td></td>
</tr>
<tr>
<td>Woodstock 1995 (2)</td>
<td>NS</td>
</tr>
<tr>
<td>Harrow 1996 (1)</td>
<td>*</td>
</tr>
<tr>
<td>Harrow 1996 (1) vs</td>
<td></td>
</tr>
<tr>
<td>Woodstock 1995 (2)</td>
<td>*</td>
</tr>
</tbody>
</table>

*Comparisons between locations and years followed by an * indicate differences (P < 0.05).

$Y_{wf}$ is weed-free yield, $I_1$ is percent yield loss caused by pigweed at low densities, $I_2$ is percent yield loss caused by barnyardgrass at low densities, and $A$ is the asymptotic yield loss at high weed densities of both species.

*Timing indicates weed emergence relative to soybean emergence: (1) at soybean emergence (VE), (2) at the V2 to V3 stage of soybean.
Table 4. Conversion factors used to determine pigweed equivalents for each location, year, and time of emergence.

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Timing</th>
<th>$I_2 / I_1^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woodstock</td>
<td>1995</td>
<td>1</td>
<td>0.14</td>
</tr>
<tr>
<td>Woodstock</td>
<td>1995</td>
<td>2</td>
<td>0.21</td>
</tr>
<tr>
<td>Harrow</td>
<td>1995</td>
<td>1</td>
<td>0.40</td>
</tr>
<tr>
<td>Woodstock</td>
<td>1996</td>
<td>1</td>
<td>0.17</td>
</tr>
<tr>
<td>Harrow</td>
<td>1996</td>
<td>1</td>
<td>0.075</td>
</tr>
</tbody>
</table>

*Timing indicates weed emergence relative to soybean emergence: (1) at soybean emergence (VE), (2) at the V2 to V3 stage of soybean.

*Ratio of barnyardgrass and pigweed I values which determines the conversion factor for creating pigweed equivalents from actual barnyardgrass densities. A ratio value of 1.0 indicates equal competitive ability between species.
Table 5. Pigweed equivalent densities corresponding to weed threshold levels of 2.5, 5.0, and 10% soybean yield loss, for each location, year, and time of weed emergence. Values based on equation 6.

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Timing</th>
<th>2.5%</th>
<th>5.0%</th>
<th>10.0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woodstock</td>
<td>1995</td>
<td>1</td>
<td>0.21</td>
<td>0.44</td>
<td>0.97</td>
</tr>
<tr>
<td>Woodstock</td>
<td>1995</td>
<td>2</td>
<td>0.8</td>
<td>1.75</td>
<td>4.3</td>
</tr>
<tr>
<td>Woodstock</td>
<td>1996</td>
<td>1</td>
<td>0.47</td>
<td>0.98</td>
<td>2.15</td>
</tr>
<tr>
<td>Harrow</td>
<td>1995</td>
<td>1</td>
<td>0.22</td>
<td>0.43</td>
<td>0.93</td>
</tr>
<tr>
<td>Harrow</td>
<td>1996</td>
<td>1</td>
<td>0.13</td>
<td>0.26</td>
<td>0.56</td>
</tr>
</tbody>
</table>

*Timing indicates weed emergence relative to soybean emergence: (1) at soybean emergence (VE), (2) at the V2 to V3 stage of soybean.*
Figure 1. Percent soybean seed yield loss as a function of pigweed equivalent density and time of weed emergence (1st emergence date = □—□, 2nd emergence date = •—•), at Woodstock and Harrow in 1995 and 1996. Points represent mean observed values, and lines are the result of fitting the data to equation 6.
Contributions. This multiple weed species interference study has expanded our knowledge of the biology of two prolific agricultural weed species in Ontario, generated weed threshold information for a multiple weed species complex in soybean, and provided a foundation for further crop-weed modelling research. This research has become an important component in the expansion of an IWM system for Ontario agriculture.

The primary result of this research found pigweed to be more competitive than barnyardgrass in a soybean crop across differing environmental conditions, years, and times of weed emergence. This confirms previous research in that weed emergence relative to the crop is essential in determining the magnitude of crop yield loss. Threshold levels for weeds emerging with a crop are generally lower than the weed densities found in most fields. The result is a need for control of weeds emerging with a crop. Weeds that emerge after a crop, can often remain in the field and not cause a significant crop yield loss depending on type of crop, weed species, weed density, and environmental conditions. Based on the results from our study, pigweed should be given a higher priority for control than barnyardgrass in soybean when both weeds co-exist in a multi-species environment.

The competitiveness of pigweed and barnyardgrass in this study was
determined by their effects on final crop yield. Other methods for determining weed competitiveness against a crop include leaf area and plant biomass. Leaf area and plant biomass measurements (data not shown) were taken from all single- and multi-species treatments at the fourth reproductive stage (R4) of soybean development in 1995 and 1996 at Woodstock. Leaf area and biomass was also taken at the R1 stage of soybean development in 1996 at Woodstock. Further analysis of these data is required to determine the competitive abilities of pigweed and barnyardgrass from a leaf area or plant biomass perspective.

Detailed records of crop and weed phenological growth stages as outlined by Lancashire et al. (1991) (BBCH code) and the heights of crop and weeds were taken on a weekly basis at Woodstock in 1995 and 1996 (data not shown). These data combined with the aforementioned leaf area and biomass data can be used in future crop-weed modelling efforts in the areas of weed emergence, leaf area development, and multiple weed species interference.

Limitations. The multiple weed species model developed by Swinton et al. (1994a,b) does not account for more than one timing of weed emergence. In this study, each weed emergence timing was treated as a separate data set. The current model should be expanded for future multiple weed species interference studies involving more than one weed emergence timing. A second limitation of this study is that barnyardgrass plant numbers were restricted at the second emergence timing, due to inadequate moisture and poor soil coverage during and after seed sowing. To ensure adequate weed stands at later
emergence timings, seeds should be sown in a 2-3 cm trough and thoroughly covered with soil to ensure contact with soil moisture. Another limitation involves the pigweed and barnyardgrass density pairings in the multi-species treatments. Future multiple weed species interference studies should use weed density pairings as outlined by Toler et al. (1996). In this multi-species study, smooth pigweed and johnsongrass were thinned to achieve densities of 16 and all possible combinations of 0, 1, 2, 4, and 8 plants 4.6 m⁻¹ of row. The improvement in the Toler et al. (1996) experimental design is that identical densities for both single- and multi-species treatments are used. This design would better determine where the area of influence from the different species begin to overlap, and more clearly examine the concept of additivity at 'low' weed densities.

**Future Research.** Empirical threshold models in general (whether single- or multi-species) have several limitations. These models cannot be used to explain why the levels of observed interference occur (Swanton et al. 1997). Parameter estimates generated from empirical research are specific to the data set from which they were derived and lack predictability under different environmental conditions. Mechanistic models of crop-weed competition quantify the various physiological and physical processes underlying crop and weed growth as well as the effect of environmental and cultural factors on these processes (Swanton et al. 1997). Mechanistic models represent an opportunity to shift weed science from a descriptive to a predictive approach. However, empirical studies remain
the driving force behind advances in mechanistic modelling as well as the future of weed science.
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retroflexus) and barnyardgrass (Echinochloa crus-galli) interference in potatoes (Solanum tuberosum). Weed Sci. 38:338-343.


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Appendix 1. SAS program to obtain the nonlinear regression fit (PROC NLIN) and the pure error (PROC GLM) for the Swinton et al. (1994b) multiple weed species model (equation 5) for Woodstock 1995.

OPTIONS LS=74;
*TEST FOR LACK OF FIT OF THE NONLINEAR MULTIPLE WEED SPECIES SWINTON MODEL ON WOODSTOCK 1995 1ST TIMING DATA;
DATA ONE;
INPUT YEAR SPP DENS REP SYLD PW BYG;
*YLSS=(1-(SYLD/3700))*100;
CARDS;
;
PROC GLM;
CLASS REP PW BYG;
MODEL SYLD = REP PW BYG;
RUN;

PROC NLIN;
PARMS YWF=3700 I1=13 I2=2 A=64;
V = I1*PW + I2*BYG + A;
MODEL SYLD = YWF*(1-((I1*PW + I2*BYG)/
                   (100*(1+((I1*PW + I2*BYG)/A)))));
DER.YWF=(A**2/(100*V))-(A/100)+(1);
DER.I1=-(A**2)*PW*YWF)/(100*(V**2));
DER.I2=-(A**2)*BYG*YWF)/(100*(V**2));
DER.A=-(YWF*(V-A)**2)/(100*(V**2));
RUN;

Appendix 2. Method to test for lack of fit of the nonlinear regression model.

\[
\frac{[NLIN \text{ RSS} - GLM \text{ RSS}]}{NLIN \text{ df} - GLM \text{ df}} \div \frac{GLM \text{ RMS}}{LACK \text{ OF FIT error}} = \frac{LACK \text{ OF FIT df}}{RMS}
\]

Simple F-test to compare above value to an F-table value.

\(H_0\): no lack of fit

\(H_A\): lack of fit
Appendix 3. SAS program to compare the estimated parameters from the nonlinear regression fit of the Swinton et al. (1994b) multiple weed species model (equation 5) for Woodstock in 1995 and 1996.

OPTIONS LS=74;
*ANALYSIS OF MULTI-SPECIES SWINTON MODEL PARAMETER ESTIMATES USING DUMMY VARIABLE ANALYSIS WITH DERIVATIVES FOR W 1995 AND W 1996 DATA;
*YEAR 1 - 1995 YEAR 2 - 1996;
DATA ONE;
INPUT YEAR SPP DENS REP SYLD PW BYG;
IF YEAR = 1 THEN Z = 1;
IF YEAR = 2 THEN Z = 0;
CARDS;
;
PROC NLIN;
PARMS YWF=3800 I1=15 I2=2 A=60 S0=448 S1=6.7 S2=0.75 S3=5.6;
V = (I1+S1*Z)*PW + (I2+S2*Z)*BYG + (A+S3*Z);
MODEL SYLD = (YWF+S0*Z)*(1-(((I1+S1*Z)*PW + (I2+S2*Z)*BYG)/(100*(1+(((I1+S1*Z)*PW + (I2+S2*Z)*BYG)/(A+S3*Z))))));
DER.YWF=((A+S3*Z)**2/(100*V))-(A+S3*Z)/100)+(1);
DER.I1=-(((A+S3*Z)**2)*PW *(YWF+S0*Z))/(100*(V**2));
DER.I2=-(((A+S3*Z)**2)*BYG*(YWF+S0*Z))/(100*(V**2));
DER.A=-(YWF+S0*Z)*(V-(A+S3*Z)**2)/(100*(V**2));
RUN;
Appendix 4. SAS program to run the Swinton et al. (1994b) multiple weed species model with derivatives on Woodstock 1995 1st timing field data.

OPTIONS LS=74;
*MULTI-SPECIES SWINTON MODEL RUN WITH DERIVATIVES ON WOODSTOCK 1995 1ST TIMING DATA;
DATA ONE;
INPUT YEAR SPP DENS REP SYLD PW BYG;
YLSS=(1-(SYLD/3700))*100;
CARDS;
;
PROC SORT DATA=ONE;
BY SPP DENS REP;
PROC NLIN;
   P ARMS YWF=3700 I1=13 I2=2 A=64;
   V = I1*PW + I2*BYG + A;
   MODEL SYLD = YWF*(1-(((I1*PW + I2*BYG)/(100*(1+((I1*PW + I2*BYG)/A)))));
   DER.YWF=(A**2/(100*V))-(A/100)+(1);
   DER.I1=-(A**2)*PW*YWF/(100*(V**2));
   DER.I2=-(A**2)*BYG*YWF/(100*(V**2));
   DER.A=-(YWF*(V-A)**2)/(100*(V**2));
RUN;
Appendix 5. Observed weed-free soybean seed yields and parameter estimates (±S.E.) for single species pigweed treatments. Parameter estimates were obtained by fitting the data for each location, year, and time of weed emergence to Cousens’ (1985a) simple rectangular hyperbolic model (equation 1).

<table>
<thead>
<tr>
<th>Loc.</th>
<th>Yr.</th>
<th>Tim.</th>
<th>weed-free yld.</th>
<th>Obs. mean</th>
<th>Parameter estimates²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>kg ha⁻¹</td>
<td>Y₀ [kg ha⁻¹]</td>
</tr>
<tr>
<td>W</td>
<td>1995</td>
<td>1</td>
<td>3652 (183)</td>
<td>3717 (144)</td>
<td>13.7 (6.4)</td>
</tr>
<tr>
<td>W</td>
<td>1995</td>
<td>2</td>
<td>3652 (183)</td>
<td>3693 (109)</td>
<td>2.3 (2.8)</td>
</tr>
<tr>
<td>W</td>
<td>1996</td>
<td>1</td>
<td>3149 (229)</td>
<td>3295 (157)</td>
<td>6.7 (4.3)</td>
</tr>
<tr>
<td>W</td>
<td>1996</td>
<td>2</td>
<td>3149 (229)</td>
<td>3165 (155)</td>
<td>3.7 (12.4)</td>
</tr>
<tr>
<td>H</td>
<td>1995</td>
<td>1</td>
<td>4016 (86)</td>
<td>3990 (114)</td>
<td>12.5 (6.7)</td>
</tr>
<tr>
<td>H</td>
<td>1996</td>
<td>1</td>
<td>1986 (257)</td>
<td>1957 (148)</td>
<td>63.0 (33)</td>
</tr>
</tbody>
</table>

²Y₀ represents predicted weed-free yield, I is the percent yield loss caused by pigweed as density approaches zero, and A represents the asymptotic yield loss at high pigweed densities.

⁵Timing indicates weed emergence relative to soybean emergence: (1) at soybean emergence (VE); (2) at the V2 to V3 stage of soybean.
Appendix 6. Observed weed-free soybean seed yields and parameter estimates (±S.E.) for single species barnyardgrass treatments. Parameter estimates were obtained by fitting the data for each location, year, and time of weed emergence to Cousens’ (1985a) simple rectangular hyperbolic model (equation 1).

<table>
<thead>
<tr>
<th>Loc.</th>
<th>Yr.</th>
<th>Tim. (^b)</th>
<th>weed-free yld.</th>
<th>Obs. mean</th>
<th>Parameter estimates(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Y(_w)</td>
<td>(l)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>kg ha(^{-1})</td>
<td>kg ha(^{-1})</td>
</tr>
<tr>
<td>W</td>
<td>1995</td>
<td>1</td>
<td>3652 (183)</td>
<td>3663 (132)</td>
<td>1.2 (0.4)</td>
</tr>
<tr>
<td>W</td>
<td>1995</td>
<td>2</td>
<td>3652 (183)</td>
<td>——</td>
<td>lack of fit</td>
</tr>
<tr>
<td>W</td>
<td>1996</td>
<td>1</td>
<td>3149 (229)</td>
<td>——</td>
<td>lack of fit</td>
</tr>
<tr>
<td>W</td>
<td>1996</td>
<td>2</td>
<td>3149 (229)</td>
<td>3139 (209)</td>
<td>0.2 (1.7)</td>
</tr>
<tr>
<td>H</td>
<td>1995</td>
<td>1</td>
<td>4016 (86)</td>
<td>4018 (133)</td>
<td>3.8 (1.0)</td>
</tr>
<tr>
<td>H</td>
<td>1996</td>
<td>1</td>
<td>1986 (257)</td>
<td>1988 (4)</td>
<td>1.7 (2.9)</td>
</tr>
</tbody>
</table>

\(^a\)Y\(_w\) represents predicted weed-free yield, \(l\) is the percent yield loss caused by barnyardgrass as density approaches zero, and \(A\) represents the asymptotic yield loss at high barnyardgrass densities.

\(^b\)Timing indicates weed emergence relative to soybean emergence: (1) at soybean emergence (VE); (2) at the V2 to V3 stage of soybean.
THE END