Chapter 4
Plant Morphology and the Critical Period of Weed Control

J. Anita Dille

Abstract The critical period of weed control (CPWC) provides a time frame in the life cycle of the crop for scouting or sensing weed populations and making weed control applications to prevent crop yield losses. This time frame is relatively early in the growing season for a given crop. Thus, newly emerged and small weed seedlings need to be observed prior to the start of the CPWC. Morphological characteristics of these seedlings are diverse and influence the ability to sense the seedlings at a given time, and account for the changes that have occurred over time. Understanding the population dynamics for different weed species, that is, emergence timing relative to the crop, types of cotyledons and leaf arrangements, and rates of leaf appearance and stem elongation, better scouting or sensing methods can be designed prior to the start of the CPWC. The development of new automated technologies must take into account changing morphology of weed seedlings early in the life cycle of the crop. Crop management practices influence the types and numbers of weed species present and thus can change the beginning and end of the CPWC and the timing for scouting and control.

1 Introduction

When developing weed control strategies, knowledge of plant biology is one of the most important factors. Without an understanding of the changes that occur during plant growth and development, most weed control practices will result in less than satisfactory control. This chapter will discuss the basics of weeds in cropping

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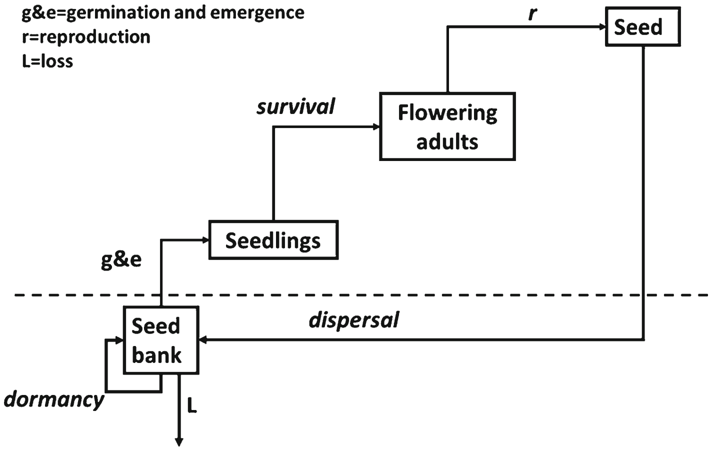


Fig. 4.1 Population dynamics of an annual weed species showing stages (*boxes*) and transitions (*arrows*) among stages. *Dashed line* indicates above and below soil surface

systems from the perspective of a weed scientist. The focus will be on weed morphology and the timing for implementation of critical weed control measures. In addition, the importance of an integrated weed management (IWM) approach will be emphasized.

Life cycles of weed species are described as summer annuals, winter annuals, biennials, or perennials (Ross and Lembi 2007). Summer annuals will emerge in the spring of the year and grow through the summer until fall when they produce seed and die, while winter annuals tend to emerge in the fall and overwinter to flower, set seed, and die in the spring. Biennials require 2 years to complete their life cycle from seedling to new seed, and perennials live longer than 2 years.

Population dynamics of a weed species are described using a series of stages and transitions that a plant goes through during a year. Stages are those observable conditions of a plant such as seed, seedling, and flowering plant, while transitions are rates of germination and emergence, proportion of seedlings that survive to become flowering plants, and rate of reproduction by flowering plants to produce new seed (Fig. 4.1). With annual weed species, the seed is the key stage in order for the population to perpetuate into the following year. Anderson (2005) highlighted three stages and transitions to target for weed control, that is, (1) enhancing the natural loss (L) of weed seeds in the soil seed bank, (2) reducing weed seedling establishment (survival), and (3) minimizing seed production by individual plants that survive to maturity (r) (Fig. 4.1).

Each stage in the population dynamics cycle can be influenced with one or more weed control tactics as part of an IWM strategy. Tactics include cultural, biological, mechanical, and chemical practices. For example, cultural tactics include rotation design and crop sequencing, use of no-tillage practices, crop residue management, and developing competitive crop canopies via fertilization strategies and row spacing/seeding rate adjustments (Anderson 2005; Swanton and Weise 1991).

Mechanical or physical control tactics include any preplant or in-crop tillage practice, flaming, or use of mulches to physically reduce weed seedling establishment and growth. Chemical practices include application of preemergence and postemergence herbicide products that can provide residual, contact, or systemic activity. Many of these tactics can be implemented using automated technologies that might provide for more accurate placement of a control practice while reducing environmental and economic impacts of weed control.

Within the framework of the weed population dynamics cycle, weed control is often implemented to reduce weed seedling establishment either as seed germinates and emerges (g&e) or just after emergence (survival) (Fig. 4.1). The type of knowledge needed to effectively implement weed control practices varies depending on ecological, economical, or efficacy-based perspectives. From an ecologically based perspective, knowledge is needed on weed species germination and emergence timing (relative to the crop), on weed seedling growth rate including the production of leaves and elongation of stems within a given crop, and on impacts of a given crop production system on weed seedling growth and development. From an economically based perspective, it is important to know the potential yield loss, reduction in crop quality, or impact of future weed seed production as a result of those weeds. A combination of ecology and economics determines the critical period of weed control (CPWC) which is defined as the time period in the crop growth cycle when weeds must be controlled to protect future crop yield (Knezevic et al. 2002). The CPWC is useful as a time frame for making decisions on the scouting for weeds and timing of application of weed control practices. From an efficacy-based perspective, knowledge is required on the maximum size when weed seedlings can still be effectively controlled with a given weed control tactic. For example, postemergence herbicides work more effectively on small, actively growing weed seedlings, and maximum size limitations are often provided on herbicide labels. The use of mechanical tools such as a rotary hoe requires weed seedlings to be just emerging through the soil surface, or the weeds will be too large for effective control with this tool. Weed seedlings can be somewhat larger if using an inter-row cultivator. Other crop production practices that influence weed emergence and how weeds change through time include crop species present, row spacing and crop seeding rates, fertility practices and tillage systems, and any previous weed control practices implemented. Depending on choice of weed control practice, one needs to be able to identify or “sense” the weed species before it reaches this maximum size and needs to be able to effectively control these plants, preferably during the CPWC.

The overall goal of this chapter is to highlight the challenge of observing weeds at a resolution relevant for both automated weed control (sensing and control) and in a timely manner with respect to minimizing impacts on crop growth and development that result in yield losses. Key concepts will be (1) when do weeds emerge, (2) what do they look like at emergence and as they grow, (3) how quickly do canopy features of weed species change through time, (4) when do these weeds impact crop yield as described using the critical period of weed control, and (5) what is the influence of crop production practices on weed emergence and growth.

2 Weed Emergence Timing

Within an agricultural field, it is the norm rather than the exception to have some weed species emerging early and others later in the growing season. There is a continuum of emergence that can be described, such as when a weed species begins to emerge, how rapidly individual seedlings appear, and for how long they continue to emerge during the growing season. Emergence patterns can be determined through regular weekly census of naturally occurring weed populations. For example, four common summer annual weeds in corn and soybean fields in Iowa had velvetleaf (*Abutilon theophrasti*) emerging the earliest, while common waterhemp (*Amaranthus rudis*) emerged later, and it had a longer emergence period than woolly cupgrass (*Eriochloa villosa*), giant foxtail (*Setaria faberi*), or velvetleaf (Hartzler et al. 1999). The pattern of kochia (*Kochia scoparia*) seedling emergence in the central Great Plains was primarily from early April to late June, whereas green foxtail (*Setaria viridis*), wild-proso millet (*Panicum miliaceum*), and redroot pigweed (*Amaranthus retroflexus*) began emerging in late May and continued until August (Anderson and Nielsen 1996).

The rate of emergence varies by species and can occur in single or multiple peaks. Some weed species, such as kochia, will have a majority of seedlings emerging within 7 days of initiation (Dille et al. 2012), while other weed species, such as common waterhemp, will have a prolonged time period over which seedlings appear (Hartzler et al. 1999). Woolly cupgrass consistently had its initial emergence later than many species, but nearly all seedlings occurred within 3 weeks after initiation. For other weeds, such as velvetleaf, giant foxtail, and common waterhemp, emergence peaks are typically influenced by rainfall events (Hartzler et al. 1999). Depending on the year and related rainfall events, the total number of weed seedlings that will emerge varies, but typically, the initial emergence for a given weed species begins at approximately the same time each year.

When describing a weed community made up of many species, there may be several emergence peaks as well. For example, kochia and Russian thistle (*Salsola tragus*) were the main species emerging during the first peak early in the year, whereas green foxtail, wild-proso millet, and pigweed species (*Amaranthus* spp.) predominated in the second peak that occurred later in the growing season (Fig. 4.2). In this example, the two peaks represented a majority (67 %) of the total weed seedling emergence. The emergence pattern of this weed community was consistent among years, and crop rotation or tillage system did not change the pattern, only total number of seedlings that emerged (Anderson 1994).

Knowing the seedling emergence pattern of a weed population or community provides insight as to what crop should be planted and options for weed control. For example, Anderson (2005) overlaid the emergence pattern of the weed community in the Great Plains with the timing of corn or sunflower planting (Fig. 4.3). Corn is normally planted in early May, whereas sunflower is planted 3–4 weeks later. This delay with planting provides producers with an additional opportunity to control 35–50 % of potential weed seedlings before planting sunflower; otherwise, these weed seedlings emerge in corn and require post-planting control. In another example in

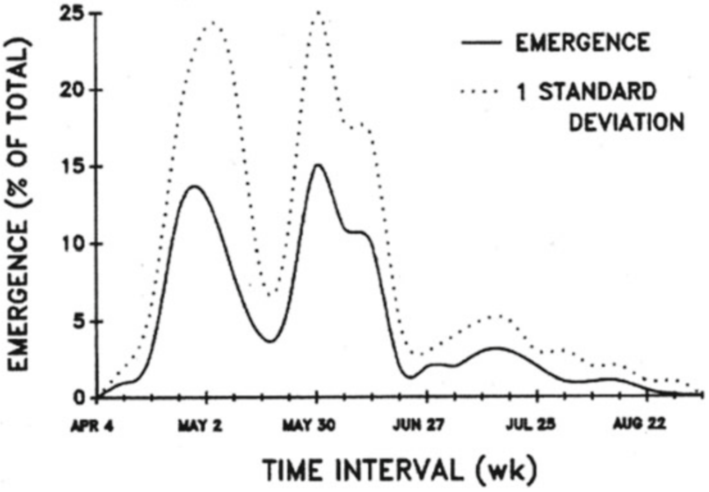


Fig. 4.2 Seedling emergence pattern of a weed community (*solid line*) at Akron, CO averaged over 7 year 1987–1993. *Dotted line* represents 1 standard deviation (Reprinted with permission from Anderson 1994)

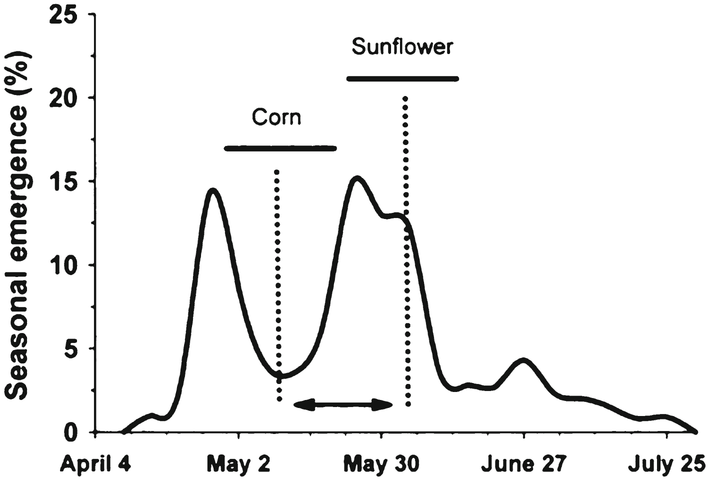


Fig. 4.3 Seedling emergence pattern of a weed community at Akron, CO. Data averaged across 7 year. *Horizontal lines* underneath corn and sunflower represent normal planting dates for these crops. The *double-ended arrow* highlights the potential difference in seedling emergence between average planting dates of these crops (Reprinted with Permission from Anderson 2005)

Iowa, optimal corn planting dates are between April 15 and May 9 (Elmore 2012), and optimal soybean planting dates are after April 25 (Pedersen 2013). The following weed species are problems in these two crops because the initial emergence of velvetleaf is on April 28, followed by woolly cupgrass on May 2, giant foxtail on May

15, and common waterhemp on May 22 in Iowa (Hartzler et al. 1999). These data highlight the need to know when different weed species emerge in relation to the crop being planted.

3 Weed Emergence and Growth Characteristics

As weed species germinate and emerge from the soil, the first plant part that is exposed above the soil surface is usually the cotyledons. This immediately impacts that amount of green plant material that could be observed and sensed. If the plant is a flowering annual weed species, it could be a dicotyledon with two cotyledons (broadleaf) or it could be a monocotyledon with one cotyledon (grass or grasslike). Many weed species can be easily identified based on their cotyledon shape and size such as tall morning glory (*Ipomoea purpurea*) or Venice mallow (*Hibiscus trionum*) (Fig. 4.4). With broadleaf species, the size of cotyledons depends on size of seed from which the plant emerges. These could be categorized into general groupings of large-, medium-, and small-seeded broadleaves. Large-seeded broadleaves often include weed species such as common cocklebur (*Xanthium strumarium*), jimsonweed (*Datura stramonium*), giant ragweed (*Ambrosia trifida*), and devil's claw (*Proboscidea louisianica*). Medium-seeded broadleaves would be velvetleaf, prickly sida (*Sida spinosa*), common ragweed (*Ambrosia artemisiifolia*), and wild sunflower (*Helianthus annuus*), while small-seeded broadleaves would include species such as pigweed species, common lambsquarters (*Chenopodium album*), and kochia.

With grass or grasslike species, the size and orientation of the first leaf can influence the ability to sense these plants from above. For example, most winter annual grasses such as downy brome (*Bromus tectorum*), wild oat (*Avena fatua*), or jointed goatgrass (*Aegilops cylindrica*) have a very upright and twisting first leaf arrangement, which creates very little green area to be sensed. Some summer annual grasses have a broad and horizontally oriented first leaf such as large crabgrass (*Digitaria sanguinalis*) or foxtail species (*Setaria* spp.) so that there is more plant material to be sensed.

Fig. 4.4 Unique cotyledon shape and first true leaf for tall morningglory (*Ipomoea purpurea)* and Venice mallow (*Hibiscus trionum*) seedlings (Photos courtesy of J.A. Dille)

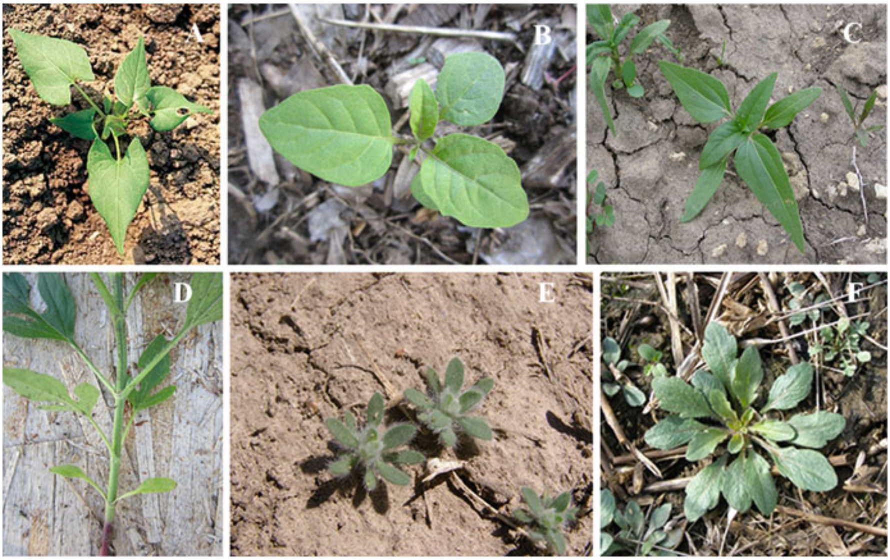
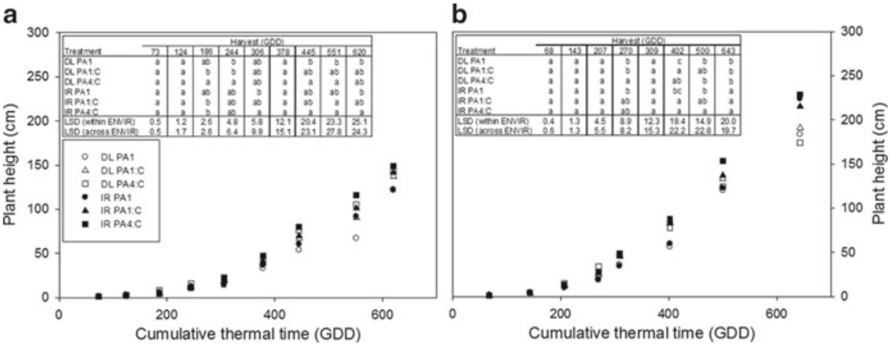


Fig. 4.5 Examples of leaf arrangement on weed seedlings. (**a**) Alternate and vining leaf arrangement of wild buckwheat (*Polygonum convolvulus*). (**b**) Alternate and upright leaf arrangement of eastern blank nightshade (*Solanum ptycanthum*). (**c**) Opposite and upright leaf arrangement of giant ragweed (*Ambrosia trifida*). (**d**) Opposite and upright leaf arrangement of common sunflower (*Helianthus annuus*). (**e**) Whorled and upright leaf arrangement of kochia (*Kochia scoparia*). (**f**) Whorled and basal arrangement of marestail (*Conyza canadensis*) (Photos courtesy of J.A. Dille)

As the first true leaves begin to appear after the cotyledons, the next observation is whether the plants produce oppositely or alternately arranged leaves as well as their rate of leaf appearance. These traits influence the total leaf area that is observed and how quickly each seedling plant increases in size in the field (for example, Fig. 4.5 a–f). Most annual broadleaves have alternate leaf arrangements so those with uniquely opposite leaf arrangement include weed species in the mint family such as henbit or occur at early growth stages for common sunflower, giant ragweed, and common ragweed, members of the sunflower family (Fig. 4.5 c and d). Subsequently, first true leaf size and arrangement of opposite or alternate leaves, together with overall plant growth habit such as upright, prostrate, or vining, influence our ability to identify and “sense” small weed plants.

4 Changes in Weed Morphology

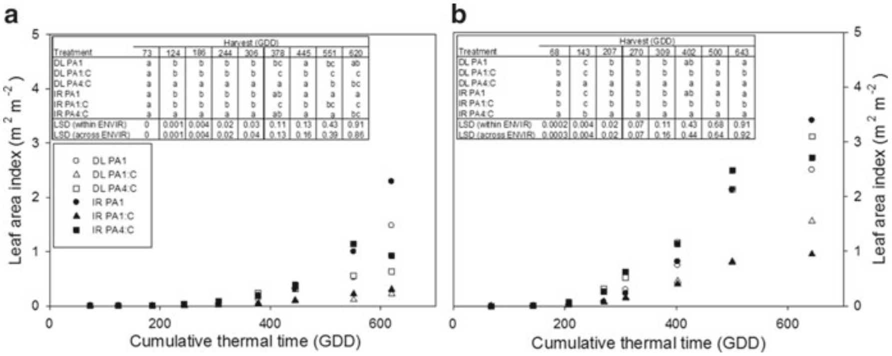
As an individual weed species develops through time, it increases in leaf number and leaf size and stem length (height) and may initiate branching. Repeatedly measuring stem length and leaf area index (leaf area/ground area, m^2/m^2) of Palmer



Treatment	Harvest (GDD) 73	124	186	244	306	378	445	551	620
DL PA1	a	a	ab	b	ab	a	b	b	b
DL PA1:C	a	a	b	b	ab	a	ab	ab	ab
DL PA4:C	a	a	a	a	ab	a	a	a	ab
IR PA1	a	a	ab	ab	b	a	ab	ab	b
IR PA1:C	a	a	b	ab	ab	a	ab	a	ab
IR PA4:C	a	a	b	ab	a	a	a	a	a
LSD (within ENVIR)	0.5	1.2	2.6	4.8	5.8	12.1	20.4	23.3	25.1
LSD (across ENVIR)	0.5	1.7	2.6	6.4	9.9	15.1	23.1	27.8	24.3

Treatment	Harvest (GDD) 68	143	207	270	309	402	500	643
DL PA1	a	a	a	b	a	c	b	b
DL PA1:C	a	a	a	b	a	a	ab	b
DL PA4:C	a	a	a	a	a	ab	b	b
IR PA1	a	a	a	b	a	bc	b	a
IR PA1:C	a	a	a	ab	a	a	ab	a
IR PA4:C	a	a	a	ab	a	a	a	a
LSD (within ENVIR)	0.4	1.3	4.5	8.9	12.3	19.4	14.9	20.0
LSD (across ENVIR)	0.6	1.3	5.5	8.2	15.3	22.2	22.8	19.7

Fig. 4.6 Palmer amaranth plant height in dryland (*DL – open symbols*) and irrigated (*IR – closed symbols*) environments grown alone (PA1) at one Palmer amaranth plant m – 1 of row and with corn at one (PA1:C) or four (PA4:C) Palmer amaranth plants m – 1 of row in 2005 (**a**) and 2006 (**b**). Letter within columns by harvest date compare means using LSD (across ENVIR) (Rule 2007)



Treatment	Harvest (GDD) 73	124	186	244	306	378	445	551	620
DL PA1	a	b	b	b	b	bc	a	bc	ab
DL PA1:C	a	b	b	b	b	c	b	c	c
DL PA4:C	a	a	a	a	a	a	a	b	bc
IR PA1	a	b	b	b	b	ab	a	a	a
IR PA1:C	a	b	b	b	b	c	b	bc	c
IR PA4:C	a	a	a	a	a	ab	a	a	bc
LSD (within ENVIR)	0	0.001	0.004	0.02	0.03	0.11	0.13	0.43	0.91
LSD (across ENVIR)	0	0.001	0.004	0.02	0.04	0.13	0.16	0.39	0.86

Treatment	Harvest (GDD) 68	143	207	270	309	402	500	643
DL PA1	b	c	b	b	b	ab	a	a
DL PA1:C	b	c	b	b	b	b	b	b
DL PA4:C	a	a	a	a	a	a	a	a
IR PA1	b	c	b	b	b	ab	a	a
IR PA1:C	b	c	b	b	b	b	b	b
IR PA4:C	a	b	a	a	a	a	a	a
LSD (within ENVIR)	0.0002	0.004	0.02	0.07	0.11	0.43	0.68	0.91
LSD (across ENVIR)	0.0003	0.004	0.02	0.07	0.16	0.44	0.64	0.92

Fig. 4.7 Palmer amaranth leaf area index in dryland (*DL – open symbols*) and irrigated (*IR – closed symbols*) environments grown alone (PA1) at one Palmer amaranth plant m – 1 of row and with corn at one (PA1:C) or four (PA4:C) Palmer amaranth plants m – 1 of row in 2005 (**a**) and 2006 (**b**). Letter columns by harvest date compare means using LSD (across ENVIR) (Rule 2007)

amaranth (*Amaranthus palmeri*) over time, with or without crop competition, shows how quickly this weed species develops early in the growing season (Figs. 4.6 and 4.7). Palmer amaranth height doubled every 60 growing degree days (GDD) from emergence to 445 or 402 GDD, which is prior to corn tasseling (Rule 2007). Palmer amaranth grew and developed at a more rapid rate than common waterhemp, redroot pigweed, and tumble pigweed (*Amaranthus albus*) when grown in common conditions in Kansas (Horak and Loughin 2000). Correct identification of weed species early is critical to knowing how quickly it will increase in size, become competitive with the crop, and reach maximum size that can limit effective weed control applications (Bensch et al. 2003; Horak and Loughin 2000; Mayo et al. 1995). A generic identification of a pigweed species can be problematic if it actually

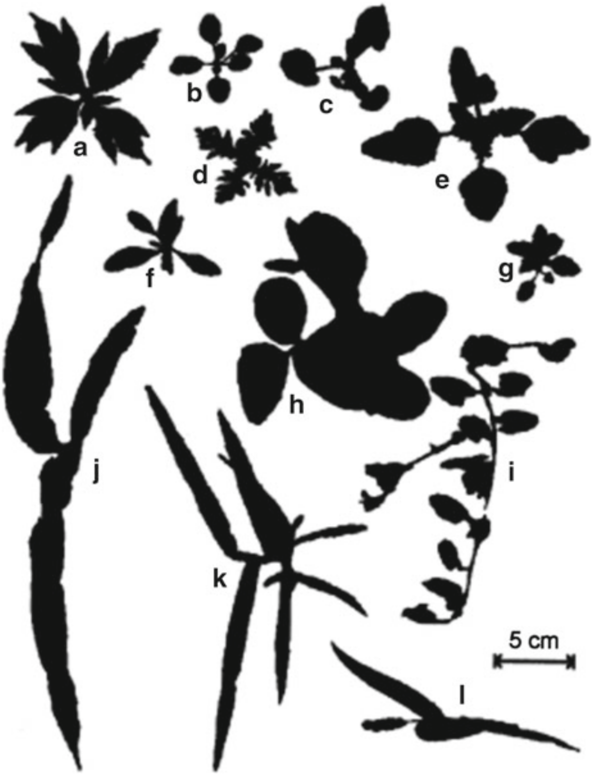
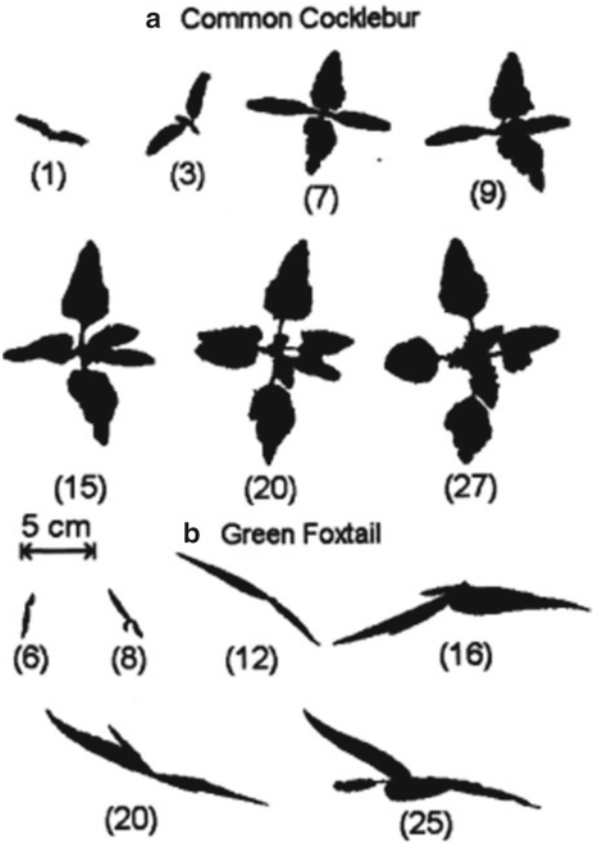


Fig. 4.8 Typical canopy shapes of various plant species 20–30 days after emergence (**a**) giant ragweed (*Ambrosia trifida*), (**b**) field pennycress (*Thlaspi arvense*), (**c**) velvetleaf (*Abutilon theophrasti*), (**d**) common ragweed (*Ambrosia artemisiifolia*), (**e**) common cocklebur (*Xanthium strumarium*), (**f**) Pennsylvania smartweed (*Polygonum pensylvanicum*), (**g**) common lambsquarters (*Chenopodium album*), (**h**) soybean (*Glycine max*), (**i**) field bindweed (*Convolvulus arvensis*), (**j**) corn (*Zea mays*), (**k**) large crabgrass (*Digitaria sanguinalis*), and (**l**) green foxtail (*Setaria viridis*) (Reprinted with permission from Woebbecke et al. 1995)

is Palmer amaranth growing at a more rapid pace than redroot pigweed, for example (Horak and Loughin 2000).

As a weed canopy develops, its geometric shape is composed of both vertical structures (stem elongation) and horizontal structures (leaf number and size, branches), which can be complex and constantly changing as the plant grows over time and with changing environmental conditions. Before the advent of most automated technologies, strategies to describe plant canopy shapes were evaluated by Woebbecke et al. (1995). Color slide photographs were taken at 2- to 4-day intervals up to 45 days after emergence of 10 common weed species as well as corn and soybean and each slide was digitized (Woebbecke et al. 1995). These digital images were used together with shape feature analysis, and the authors were able to discriminate between grasses and broadleaves at 14 and 23 days after emergence (Fig. 4.8). Canopy shape features for seedlings with few leaves are greatly affected

Fig. 4.9 Development of (**a**) broadleaf [common cocklebur (*Xanthium strumarium*)], and (**b**) grass [green foxtail (*Setaria viridis*)]. Each *number in parentheses* represents plant age, in days after emergence (Reprinted with permission from Woebbecke et al. 1995)



by the shape of the individual leaves. However, there is no guarantee that any particular shape feature will continue to work successfully as a plant classifier as the size of the plant increases. For example, the roundness value for monocots (calculated as $P^2/4\pi A$, where P is canopy perimeter (cm) and A is projected area (cm^2)) is close to one soon after emergence and makes it difficult to discriminate them from dicots. Some dicots emerged with cotyledons having a long slender shape (such as common cocklebur or jimsonweed), making separation from monocots difficult at this young age. The best separation (greater than 80 %) of monocots and dicots among this group of 10 weed species occurred after 14 days of age, corresponding to the full development the first true leaves in dicots (Woebbecke et al. 1995). It was determined that canopy shape features generally do not significantly change for dicots between ages of 10 and 23 days, while for monocots it was between ages 14 and 23 days (Fig. 4.9). During this window of time, seedlings of these 10 weed species are still small enough to be controlled effectively with most chemical options and occur early in the CPWC for most crops.

The rate of change in canopy shape will be influenced by the rate of leaf appearance, which is driven primarily by temperature in a linear relationship (Alm et al. 1988;

Cao and Moss 1989) and corresponds to the normal range of temperatures observed during the growing season. For example, Gramig and Stoltenberg (2007) determined the mean thermal time needed for the rate of appearance of each leaf for six common weed species was 37.2 GDD per leaf for giant ragweed, 34.4 GDD for velvetleaf, 17.3 GDD for redroot pigweed, 42.2 GDD for large crabgrass, 65.2 GDD for woolly cupgrass, and 34.2 GDD for wild-proso millet. Shrestha and Swanton (2007) determined the rate of leaf appearance for 4 other weed species to be 20–25 GDD per leaf for common lambsquarters, 50–100 GDD for barnyard grass, 14–25 GDD for redroot pigweed, and 33–50 GDD for wild mustard (*Sinapis arvensis*). The rate of leaf appearance for the weed species was not influenced by the crop planting date; environmental conditions (moisture and temperature) at crop planting have a greater influence on the initial rate of leaf appearance of weeds. At the time of scouting (sensing) for weed species, knowledge of how quickly a weed species produces individual leaves would allow for prediction of future ground area covered by knowing leaf size and density of the weed species in a given area.

5 Crop Losses from Weeds According to CPWC

Numerous studies have determined crop yield losses, reductions in crop quality, or inefficient harvesting due to effects of weed densities and time of weed emergence relative to the crop. These studies have provided critical threshold densities as to when to implement weed control practices. Next is to determine the best time frame to scout a crop and determine if the weed population or community is greater than this threshold. This time frame is described by the critical period of weed control (CPWC), defined as the time period during the life cycle of the crop when it must be kept weed-free to prevent yield loss due to weed competition (Knezevic et al. 2002; Swanton and Weise 1991). The CPWC can be experimentally derived by determining two components: (A) duration of weed interference and (B) weed-free period (Fig. 4.10). The time period when these two components overlap is known as the CPWC, and it has a distinct beginning (crop growth stage, CGS_x) and end (CGS_y) (Fig. 4.10).

The "duration of weed interference" (A) is the length of time weeds can be present with the crop from the time of crop planting before causing greater than the threshold level of yield loss and thus need to be controlled. The length of the "weed-free period" (B) is determined by how long the crop must be maintained weed-free before later emerging weeds that grow with the crop do not cause more than the threshold level of yield loss. The level of yield loss used to predict the beginning and end of the CPWC can range from 2 to 10 % (Hall et al. 1992; Refsell 2013; Van Acker et al. 1993) and could be selected based on cost of weed control and anticipated financial gain of controlling the weeds. The CPWC for corn, soybean, winter wheat, dry bean, canola, and lentils has been derived experimentally with the unique conditions that influence the beginning and end (Table 4.1). Zimdahl (1980, 2004) has also summarized the CPWC for many other agronomic and horticultural crops.

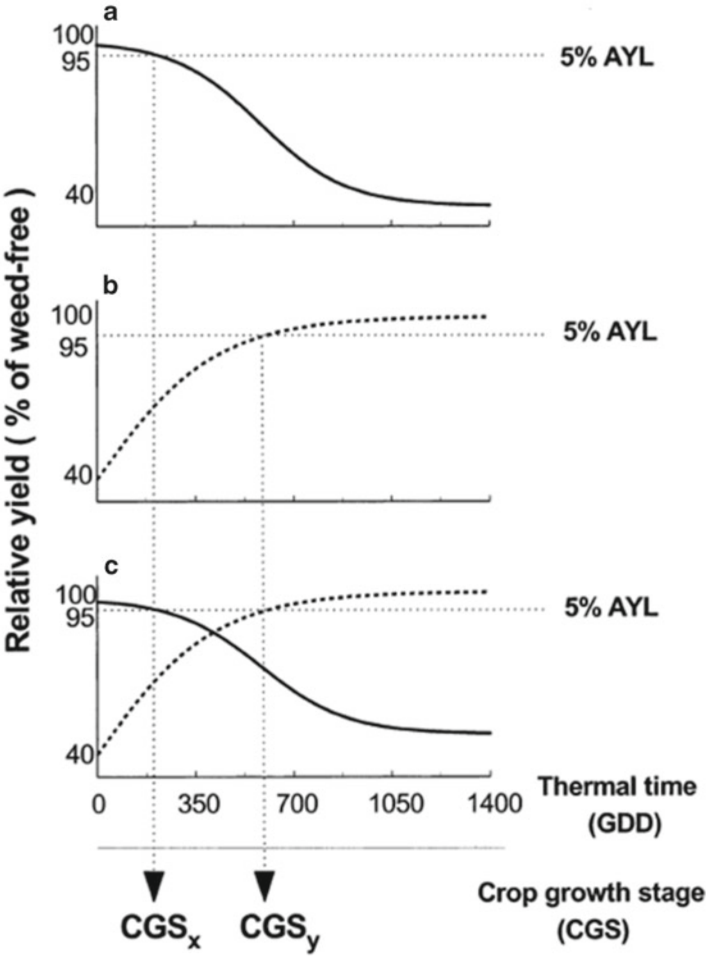


Fig. 4.10 Functional approach used for the determination of the critical period of weed control (CPWC). (**a**) The critical timing for weed removal determined from the logistic model, fit to data representing an increasing duration of weed interference. (**b**) The critical weed-free period is determined from the Gompertz model, fit to data representing an increasing duration of weed-free period. (**c**) The value of the *x* axis that corresponds to 95 % relative yield or an acceptable yield loss (*AYL*) of 5 % is determined for both curves and related to the crop growth stage (*CGS*). The CPWC is then defined as the time period between the two crop growth stages (CGS$_x$ to CGS$_y$) and represents the length of weed control required to protect crop yield from more than a 5 % yield loss (Reprinted with permission from Knezevic et al. 2002)

Thus, the CPWC provides a time frame for when to assess a weed population or community. Prior to the beginning of the CPWC, field scouting (sensing) for weeds must be initiated. It is at this time when the weed species in the field need to be identified and their density and size determined (Fig. 4.11). If field scouting for weeds reveals that there is a weed population or community of concern, and at a sufficient

Table 4.1 The beginning (duration of weed interference A) and end (weed-free period B) of the critical period of weed control as determined for different agronomic crops, locations, and anticipated yield loss threshold levels

Crop	Location	Weed species[a]	Yield threshold (%)	Duration of weed interference (A)	Weed-free period (B)	Reference
Corn	Ontario	Mixed annuals	2.5	3–6 WAP[b]	7 WAP	Hall et al. (1992)
	Texas	Johnson grass	5	3 WAP	6.5 WAP	Ghosheh et al. (1996)
	Wisconsin	Wild-proso millet	5	V2 CGS	V11 CGS	Mickelson and Harvey (1999)
	Nebraska	Mixed annuals	5	4 WAP	5–7 WAP	Evans et al. (2003)
	Ontario	Mixed annuals	2.5	2–2.5 WAP	3.5–6.5 WAP	Halford et al. (2001)
Soybean	Ontario	Mixed annuals	2.5	2–5 WAP	4 WAP	Van Acker et al. (1993)
	Illinois	Common waterhemp		2–4 WA unifoliate expansion	–	Hager et al. (2002)
	Nebraska	Mixed annuals	5	V1 (1 WAP)	–	Knezevic et al. (2003)
	Ontario	Mixed annuals	2.5	2–3 WAP	5.5–6 WAP	Halford et al. (2001)
Dry bean	Minnesota	Mixed annuals	5	3 WAP	5–6 WAP	Burnside et al. (1998)
	Ontario	Mixed annuals	3	4 WAP	7.5 WAP	Woolley et al. (1993)
Winter wheat	Kansas	Downy brome	5	19–29 WAP	5 WAP	Refsell (2013)
	England	Mixed annuals	5	4 WAP	20 WAP	Welsh et al. (1999)
Spring canola	Manitoba	Mixed annuals	10	2.5–5.5 WAP	2.5–5.5 WAP	Martin et al. (2001)
Lentil	Saskatchewan	Mixed annuals	5	5-node CGS	10-node CGS	Fedoruk et al. (2011)

[a] Johnson grass (*Sorghum halepense*), wild-proso millet (*Panicum miliaceum*), common waterhemp (*Amaranthus rudis*), downy brome (*Bromus tectorum*)

[b] *WAP* weeks after planting, *CGS* crop growth stage

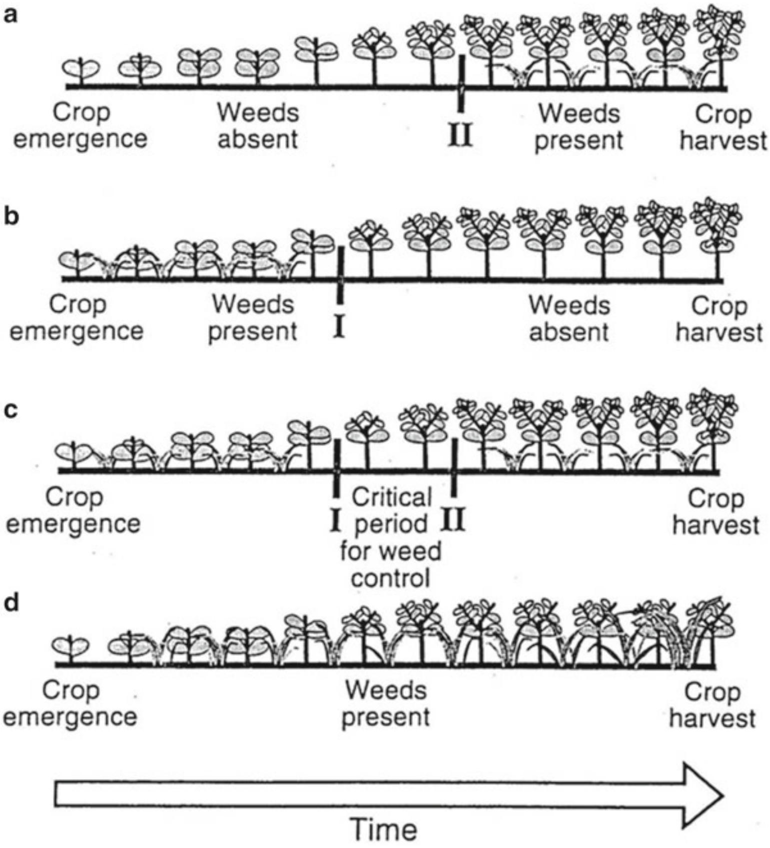


Fig. 4.11 Apparent CPWC. (**a**) If weeds are absent up to point II, crop dominance is established and yield losses do not result, even though weeds may be present subsequently. (**b**) If weeds are present for a period of time following crop emergence but are absent for the remainder of the season, yield losses do not result since, presumably, early in the season weeds are too small for competition to occur. (**c**) The combination of results from (**a**) and (**b**) leads to the critical period between points I and II, "window" of time during which weeds must be removed or suppressed to avoid crop yield loss at harvest. (**d**) Situation in which weeds are present throughout the growing season and crop yield loss results (Reprinted with permission from Radosevich et al. 2007)

density to eventually cause crop loss if left uncontrolled (greater than 2–10 % anticipated yield loss or a weed density that is greater than an economic threshold), then control measures must be implemented. Some chemical weed control practices take some time to show their effects; thus, timely removal of weeds just prior to the beginning of the CPWC is needed to ensure that no competitive weeds are present during the CPWC. Toward the end of the CPWC, late emerging weeds need to be scouted for and, based on the species identity and their density, be evaluated as to whether further control strategies need to be planned and implemented.

The start and length of the CPWC are influenced by time of weed seedling emergence relative to the crop and weed seedling density. Weeds that emerge later

Table 4.2 Mean (±SE) weed leaf numbers at the soybean (Glycine max) second trifoliate stage in relation to time of weed emergence, with data pooled over 1997, 1998, and 1999

	Weed cohort[a]		
Weed species	VE	V1	V2
Velvetleaf (*Abutilon theophrasti*)	4.6 (0.1)	–[b]	1.7 (0.1)
Common lambsquarters (*Chenopodium album*)	9.0 (0.4)	7.1 (0.2)	2.7 (0.2)
Common ragweed (*Ambrosia artemisiifolia*)	7.5 (0.2)	4.0 (0.2)	1.2 (0.1)
Common cocklebur (*Xanthium strumarium*)	5.7 (0.1)	3.7 (0.1)	2.2 (0.2)
Redroot pigweed (*Amaranthus retroflexus*)	7.4 (0.2)	3.5 (0.2)	–
Green foxtail (*Setaria viridis*)	6.8 (0.2)	3.8 (0.1)	1.3 (0.1)
Giant foxtail (*Setaria faberi*)	6.3 (0.1)	3.8 (0.2)	1.1 (0.1)
Barnyard grass (*Echinochloa crus-galli*)	6.3 (0.1)	5.2 (0.1)	2.0 (0.3)
Fall panicum (*Panicum dichotomiflorum*)	4.8 (0.1)	3.1 (0.1)	–

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[a] The VE cohort emerged before the soybean unifoliate stage; the V1 cohort emerged between the unifoliate and the first trifoliate; the V2 cohort emerged between the first and the second trifoliate

[b] Weed species not present in this cohort

beneath a crop canopy are much less competitive than those that emerge at the same time as the crop (Dieleman et al. 1995; Liphadzi and Dille 2006). It can be difficult to determine the time a weed species emerges, and this is important with respect to knowing how competitive the weed will be in the crop and its potential impact on final yields. A scout can compare the number of leaves of a weed species and the corresponding growth stage of the crop to determine when it might have emerged (Weaver 2003). For example, in Ontario, Canada, the CPWC for soybean is between the first and third trifoliate (V1 to V3). By the second trifoliate growth stage, velvetleaf emerging with soybean had an average of 4.6 (±0.1) leaves per plant, while those that emerged just prior to V2 growth stage of soybean had only 1.7 leaves per plant (Table 4.2). Common lambsquarters had 9.0 leaves when emerging at VE, compared to 7.1 leaves when emerging prior to V1 and 2.7 leaves prior to V2. Similar information was determined for corn in Ontario (Table 4.3). Timing of weed emergence and relative weed competitiveness can also be affected by a soil-applied residual herbicide applied prior to crop planting such that weed emergence is delayed, and those weeds that emerge through the herbicide may be less competitive due to physiological impact of the herbicide (Liphadzi and Dille 2006).

It is difficult to scout a field and determine an average whole-field weed density because of the spatial distribution of weed populations and communities (Dille et al. 2002; Gerhards et al. 1997; Wiles et al. 1992). Weed populations are known to be patchy throughout a field with areas of none, low, and high densities; thus, decisions about whether there is a weed species of concern and at a high enough density to require control will be dependent on location within the field (Dieleman and Mortensen 1999; Lindquist et al. 1998). The use of automated technologies allows for information to be collected on the spatial distribution of weed species densities across a field, and a whole-field average weed density is no longer needed. Implementing weed control can be linked to spatial distribution of weed species densities observed during the CPWC at any location in a field.

Table 4.3 Mean (±SE) weed leaf numbers at the corn (*Zea mays*) six-leaf stage in relation to time of weed emergence, pooled over years unless otherwise indicated

	Weed cohort[a]			
Weed species	VE (1997/1998)	VE (1999)	V1	V2
Velvetleaf (*Abutilon theophrasti*)	4.6 (0.1)	3.1 (0.1)	3.1 (0.1)	1.4 (0.1)
Common lambsquarters (*Chenopodium album*)	8.5 (0.2)	–	3.4 (0.2)	1.7 (0.1)
Common ragweed (*Ambrosia artemisiifolia*)	7.3 (0.2)	5.6 (0.2)	–	2.1 (0.2)
Giant ragweed (*Ambrosia trifida*)	7.1 (0.2)	4.7 (0.2)	–	1.9 (0.1)
Common cocklebur (*Xanthium strumarium*)	8.1 (0.2)	4.9 (0.2)	4.1 (0.2)	3.0 (0.2)
Redroot pigweed (*Amaranthus retroflexus*)	8.6 (0.2)	4.9 (0.2)	–	2.5 (0.1)
Green foxtail (*Setaria viridis*)	6.7 (0.2)	4.1 (0.3)	–	3.1 (0.1)
Giant foxtail (*Setaria faberi*)	6.7 (0.1)	4.9 (0.2)	–	3.1 (0.1)
Barnyard grass (*Echinochloa crus-galli*)	6.7 (0.1)	4.7 (0.1)	–	3.4 (0.1)
Fall panicum (*Panicum dichotomiflorum*)	–[b]	–	4.1 (0.2)	1.4 (0.1)

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[a] The VE cohort emerged before the corn two-leaf stage; the V1 cohort emerged at the corn two- to three-leaf stage; the V2 cohort emerged at the corn four- to five-leaf stage

[b] Weed species not present in this cohort

Based on economic analysis, the threshold weed density is often very low (1–5 plants m^{-2}), which might trigger the decision to implement weed control. The challenge is being able to sense and not miss these yield-impacting low densities. Armstrong et al. (2007) evaluated the use of early season multispectral images to detect low densities of common lambsquarters seedlings during the CPWC in corn. Aerial multispectral images (12–16 cm pixel resolution) were taken 18–19 and 32 days after planting in two different field studies. This resolution was much higher than previous studies which often used 0.5–1 m^2 pixel resolutions (Armstrong et al. 2007). However, with the technology at that time, they determined that corn and common lambsquarters could not be reliably detected and differentiated at either field site when weeds were 9 cm or less in height. Economic threshold densities (2 and 4 plants m^{-2}) of common lambsquarters could be distinguished from weed-free plots at one location when weeds were 17 cm in height, but unfortunately, this height was beyond that recommended on the herbicide label for glyphosate application. As technologies continue to develop, they must be able to detect very small weed seedlings before the beginning of the CPWC.

6 Crop Management and Weed Control Practices Influence the CPWC

Numerous crop management factors including the weed control practices that are already implemented can influence the beginning and end of the CPWC (Evans et al. 2003; Knezevic et al. 2002; Martin et al. 2001). Knowledge of these factors can be used to fine-tune the timing of weed scouting just prior to or during the CPWC and thus assist in determining if postemergence weed control practices are necessary to prevent a certain level of crop loss. Examples of factors include crop species present, time of crop planting, row spacing and crop seeding rates, fertility practices, and use of soil-applied residual herbicides that affect the beginning or end of the CPWC.

Crop species and its corresponding time of planting influence what weed species will co-occur in the field. A crop with rapid canopy development and row closure relative to the weed delays the beginning of the CPWC. Martin et al. (2001) observed that early seeding of canola resulted in the need for a somewhat longer weed-free period (delayed end of CPWC) because field operations were conducted relatively early in the emergence period of the weeds resulting in higher weed infestation levels for a longer time. As soybean row spacing narrowed from 76 to 19 cm, the beginning of the CPWC was delayed from V1 to V3 growth stage, highlighting that the soybean crop was developing a more competitive canopy against the weed population present (Knezevic et al. 2003). As soil N application increased from 0 to 120 kg N ha^{-1}, the start of the CPWC was delayed from V1 to V6 growth stage of corn in a Nebraska study (Evans et al. 2003; Knezevic et al. 2002).

In general, the duration of weed interference, or beginning of the CPWC, will be delayed if soil resources are abundant, the crop establishes quickly, and the weeds grow at a reduced rate. Whereas it will begin earlier if the soil resources are low, the crop establishes slowly, weed densities are high, and the weed species present grow at a rapid rate. In a similar fashion, the end of the weed-free period is short if the crop establishes quickly and is long if the crop establishes slowly. In general, develop a crop canopy that is more competitive against later emerging weeds.

7 Conclusions

The CPWC provides a time frame for when to observe and actively manage weed populations or communities in crop fields. With correct and timely observations, a combination of ecological, economic, and efficacy-based information and knowledge should be used to make weed management decisions. The CPWC occurs relatively early in the cropping season when weeds tend to be small, thus requiring improved ability for detection at a young age. Advanced technology is being developed to identify weeds with greater precision and accuracy (see Chap. 5). The use of the technology must account for variation in weed and crop growth and spatial variation in individual plants and weed populations. Knowing the conditions of weeds (e.g., growth stage) and when they transition through the different stages will allow for the development and application of automated technology. Further, the CPWC will help in determining the speed at which automated weed control systems must be able to move through the field and cover large hectares that are not static but dynamic biological systems.

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