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Revisiting the concept of the critical period of weed control

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Abstract

Weeds are a major biotic constraint to the production of crops. Studies on the critical period of weed control (CPWC) consider the yield loss due to the presence of all weeds present in the crop cycle. The CPWC is the time interval between the critical timing of weed removal (CTWR) and the critical weed-free period (CWFP), and the weed presence before and after the extremes of CTWR and CWFP may not significantly reduce crop yield. The crop yield is taken into consideration and weed density or biomass of individual weeds (annual or perennial) is not so important while calculating the CPWC. Only weed density or biomass is considered for calculating weed control efficiency of a particular management practice for which the weed seed bank is also a criterion. However, weed biomass is the outcome after competition experienced by each weed species with the fellow crop and the weeds. Consequently, the weed pressure in the subsequent season will be the cumulative effect of the preceding season too, which is unaccounted for in CPWC. It is argued that in organic farming or low-input farming systems, where herbicides are not used, the concept of CPWC can be misleading and should be avoided. It is concluded that CTWR is more meaningful than the CPWC.

Introduction

For the past five decades, since Nieto *et al.* (1968) introduced the concept of 'critical periods of the crop growth cycle for competition from weeds', it has been accepted by the international community that there are certain periods in the life cycle of a crop when weeds pose challenges to the resource competition and must be removed to accelerate crop growth; it is believed that thereafter the presence of weed species could insignificantly interfere with crop yield. In particular, the concept considers the period from sowing to a specific stage/phase of the crop to advocate cultural, mechanical or chemical weed management practices. The findings of Hauser *et al.* (1975) emphasized controlling early flushes of weeds that emerge with the peanuts. Further, a weed-free peanut crop for either 4 or 6 weeks, and sometimes only 2 weeks, resulted in near-normal yield. Moreover, the concept provided an impetus for studying the critical period of weed control (CPWC). Weeds do have a role in supporting biodiversity (Marshall *et al.*, 2003) in farmlands and are part of the primary producers and important components of the agroecosystem. CPWC could discover whether present methods of weed control are a means of maintaining the biological necessity or otherwise the biological diversity. This has been prompted by the common observation that eliminating the resource competition during this period would assure crop yield, provided other resources are not limiting.

Although CPWC has been defined in different ways, it is generally accepted that CPWC is a time interval between two components viz., the critical timing of weed removal (CTWR) and the critical weed-free period (CWFP), and the weed presence before and after CPWC should not significantly reduce crop yield (Dawson, 1986). In general, three relationships exist in CPWC (Nadeem *et al.*, 2013): (a) Maintaining the crop weed-free for the same duration that a weed infestation can be tolerated to avoid yield loss if weed control is performed during this period; (b) CWFP is lesser than CTWR so that yield loss will not occur if weeds are managed between these extremes; and (c) CWFP is of no longer duration than the CTWR, the crop must be kept weed-free between these timings to prevent yield loss. Knezevic *et al.* (2002) considered CPWC as a window for the removal of weedy species. While studying the impact of climate change on crop–weed competitive interactions (Ramesh *et al.*, 2017*a*, 2017*b*), CPWC could also be modified based on weed proliferation and/or crop–weed interaction. Although the CPWC concept has made significant contributions to integrated weed management programmes, there are multiple problems in the CPWC as illustrated below. This article is an attempt to discuss the anomalies in the CPWC and suggest suitable action for crop weed competition period estimation with examples of the crops grown in tropical and subtropical regions.

Yield loss and competition

The first issue is the per cent yield loss in relation to the duration of the competition. Even though crop–weed competition commences with crop emergence and continues to maturity (Thakral *et al*., 1989), CPWC considers only one-third of the duration in the life cycle of the crop and is based on a 5% acceptable yield loss level (Bukun, 2004) only. However, this is not universal. Yield loss from weeds is a function of crop species, growing environment, soil weed seed banks, etc. For example, a 10% yield loss due to weeds was suggested for aerobic rice (Anwar *et al*., 2012) and spring canola (Martin *et al*., 2001) since a 5% yield loss level would not be practical from an economic viewpoint. The onset of crop–weed competition in wet, direct-seeded rice (DSR) begins much earlier because of wide adaptability, quick germination and rapid growth of weeds compared to a rice crop (Elliot *et al*., 1984; Rao, 2011). Yield loss calculations are considered only for the current crop. Weeds that emerge late in the crop season after the CPWC are often considered less important (Bastiaans *et al*., 2008) but could add to the soil weed seed bank (Reisinger *et al*., 2006) and would become a yield-limiting factor in the subsequent crops in that field. A large proportion of the weed seed bank remains on or close to the soil surface after seed rain (Mário, 2017), particularly in no-till (NT) systems (Chahal *et al*., 2003; Morris *et al*., 2010). Weed seeds from weed seed banks present in the top layer of the soil germinate and seedlings grow faster than the crop, particularly in aerobic rice. The length of the CPWC in aerobic rice is expected to be longer than other systems of rice production (usually one-third of the life cycle), including conventional transplanted rice since the flooded soil environment hinders the germination of several weed species (Singh *et al*., 2016; Raj and Syriac, 2017). For example, the CPWC in wet DSR was from 12 to 60 days after sowing (DAS) (Azmi *et al*., 2007*a*, 2007*b*), so the first 60 days are accounted for crop–weed competition (Singh, 2008), while it was 20–40 days after transplanting (DAT) for transplanted rice (Mukherjee *et al*., 2008). In Sahel (West Africa), CPWC for lowland irrigated rice was 29–32 DAS in the wet season, while 4–83 DAS in the dry season (Johnson *et al*., 2004). Hence, CPWC is based on a 5% acceptable yield loss level, which can be 10% in some crops. It changes according to the crop production system (conventional, conservation or organic), weed types, crop types, soil types, climate and agronomic practice followed in that crop.

Comprehensive information on CWFP and CPWC for different crops is presented in Table 1. Genotypic differences [e.g. wheat (Huel and Hucl, 1996), maize (Saito *et al*., 2010) and sorghum (Wu *et al*., 2010)] do modify the CPWC due to their differential weed-competitive nature (Ramesh *et al*., 2017*a*, 2017*b*; Chauhan, 2020). Mahajan *et al*. (2014) found that rice genotypes PR-115 and H-97158 could not compete with weeds and were regarded as the worst weed competitors while PR-120, IR88633 and IR83927 were able to compete with weeds. Although Campos *et al*. (2016) noticed a temporal variation in CWFP in maize between years; 54 days after emergence (DAE) in the first year *v*. 27 DAE in the second year. In general, a long CPWC is an indication of more competitive weeds or less competitive crops (Ghosheh *et al*., 1996).

CTWR for different crops is presented in Table 2. While Nedeljković *et al*. (2021) could establish a narrow CTWR window of 16–19 DAE, Campos *et al*. (2016) recorded a broader window of up to 25 DAE in maize. This is so pertinent that an increase in the duration of weed interference delayed silking in maize (Page *et al*., 2012).

Table 1. Critical weed-free period (CWFP) and critical period of weed control (CPWC) for different crops[a]

Crop	CWFP	CPWC	Reference
Sesame	NA	14–64 DAE	Karnas *et al*. (2019)
Soybean	60 DAS	NA	Nimu *et al*. (2020)
Soybean	30–45 DAS	NA	Chokar and Balyan (1999)
Maize	54 DAE	29 DAE	Campos *et al*. (2016)
Maize	2–6 weeks	NA	Mahgoub *et al*. (2019)
Maize	54 DAE (first year) 27 DAE (second year)	29–54 DAE	Campos *et al*. (2016)
Sweet potato	42 DAT	NA	Seem *et al*. (2003)
Carrot (seeded in late April)	930 GDD	NA	Swanton *et al*. (2010)
Carrot caseeded in mid to late May)	414–444 GDD	NA	Swanton *et al*. (2010)
Leek	80–85 DAT	7–85 DAT	Tursun *et al*. (2007)
Potato	NA	22 DAE	Karimmojeni *et al*. (2014)
	NA	44 days (first year), 40 days (second year)	Isik *et al*. (2015)[b]
Chickpea	NA	50–69 DAS	Frenda *et al*. (2013)
French bean	NA	11–28 DAE	Stagnari and Pisante (2011)
Fababean	NA	28–33 DAS	Frenda *et al*. (2013)
Canola	NA	Spring 17–38 DAE	Martin *et al*. (2001)
Lentil	NA	5–10 node stages	Fedoruk *et al*. (2011)

DAT, days after transplanting; DAE, days after emergence; DAS, days after sowing; GDD, growing degree days; NA, not available.
[a]For 5% yield loss.
[b]For 10% yield loss.

Type of weeds and emergence patterns

Parasitic weeds, such as *Striga* spp. (Jamil *et al*., 2012) and *Orobanche* spp. (Westwood and Foy, 1999), remain unaccounted for in CPWC, as their germination pattern depends on the soil fertility and host presence (Raju *et al*., 1990). Weed emergence patterns are unpredictable; they may emerge over an extended period dictated by the prevailing weather, edaphic and crop factors (Vleeshouwers, 1997). Weed emergence patterns in spring hardly affected wheat yield but had a significant effect (4–20%

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Table 2. Critical time of weed removal (CTWR) for different crops

Crop	CTWR	Reference
Maize[a]	16–19 DAE	Nedeljković *et al.* (2021)
Popcorn[a] (maize)	V4 to V5 (four-leaf stage of popcorn to five-leaf stage of popcorn)	Barnes *et al.* (2019)
Maize[a]	25 DAE	Campos *et al.* (2016)
Soybean[b]	V4 to R1 (fourth trifoliate leaf of soybean to the beginning of flowering stage)	Mulugeta and Boerboom (2000)
Sunflower[a]	14–26 DAE or 25–37 DAE	Knezevic *et al.* (2013)
Leek[a]	7–13 DAT	Tursun *et al.* (2007)
Maize[a]	25 DAE	Campos *et al.* (2016)
Onion[a]	2–4 leaf stage	Dunan *et al.* (1996)
Potato[a]	19 DAE	Karimmojeni *et al.* (2014)
Sunflower[a]	14–26 DAE or V3 to V4 stages	Knezevic *et al.* (2013)
Field pea[a]	One or two weeks after emergence	Harker *et al.* (2001)

DAE, days after emergence.
[a]For 5% yield loss.
[b]For 3% yield loss.

yield loss) in autumn (Lotz *et al.*, 1990). The weed flora in wet DSR may vary from transplanted rice due to differences in environmental conditions (Singh *et al.*, 2008; Kumar and Ladha, 2011), and accordingly, CPWC varies. Vegetative propagules, particularly non-dormant, have a competitive advantage over crops. For example, *Cyperus esculentus* propagation is exclusively by tubers in cultivated cropland, and the deepest tubers survive the longest (Stoller *et al.*, 1979). Application of glyphosate will kill the weed above the ground but may not always kill the underground reproductive organs (ICID, 2002). Systemic herbicides (e.g. glyphosate) would be expected to be less effective where a large proportion of older tubers of *Cyperus rotundus* are present in the soil, and these herbicides fail to limit the regenerative capacity and tuber viability in the long term. Presence of *Cyperus* spp. and/or perennial weeds with vegetative propagules provide unrelenting competition for irrigated crops. The underground resource competition posed by these perennial vegetative propagules is not accounted for in the calculation of the CPWC, since mechanical weed removal is practised in CPWC calculation studies. Dhammu and Sandhu (2002) concluded that the critical period of *Cyperus iria*, an annual weed propagated by seeds, competition with transplanted rice is between 30 and 40 DAT akin to the general CPWC for transplanted rice, 20–40 DAT (Mukherjee *et al.*, 2008). The proliferation of vegetative propagules of perennial weeds even after manual removal is noticed (Schimming and Messersmith, 1988; Lemieux *et al.*, 1993), negating the concept of CPWC.

Several authors (Swanton and Weise, 1991; Baziramakenga and Leroax, 1994; Wiliams, 2006) have endorsed that CWFP (i.e. the end of CPWC) would ensure maximum yield, as late-emerging weeds would not impair the crop productivity. Albeit, late-emerging weeds would still create weed problems through their seed input in the subsequent crops (Furlong, 2016). Under organic farming situations, cultural weed management (Bastiaans *et al.*, 2008) is the prime mode of minimising weed pressure including, but not limited to, (i) enhancing crop competitive ability to weeds, and (ii) focusing on weed seed banks by either curtailing weed seedling recruitment and/or reducing the weed seed bank size (Schonbeck, 2011). Such positive effects on crop growth without weed interference, if properly translated from CPWC, might have implications in weed management. Dryland cotton growers in low-income countries resort to either pre-emergence (Deshpande *et al.*, 2006) or pre-plant incorporation of herbicides with the available soil moisture. Subsequent herbicide sprays are precipitation-dependent. In some instances, the left-over weed populations interfere with the cotton harvest, resulting in yield and quality losses (Smith *et al.*, 2000). Similarly, in peanut, the second flush of emerged weeds compete with the crop and infest the land with weed seeds (Kanagam and Chinnamuthu, 2009), resulting in heavy weed infestation in the subsequent crop.

Agro-ecology and crop management

Environmental factors or site-specific factors, dominant weeds in the region (Van Acker *et al.*, 1993), tillage (Doll *et al.*, 1992; Fortin and Hamill, 1994), and soil salinity levels (Hakim *et al.*, 2013) affect the duration of the critical period. Variations have been reported for mixed weed species, species to species, perennial weed to annual weed, and low to high weed pressure. For example, the CPWC for potatoes varied from 2 to 4 weeks after planting (Ivany, 1984, 1986) to 9 weeks after planting (Saghir and Markoullis, 1974). Intensive and non-intensive production systems do modify the CPWC, for example, 28–117 days for intensive and 38–163 days after planting for non-intensive sugarcane production systems (Kouamé *et al.*, 2014).

CPWC and row spacing have been found to influence the weed seed return to soil (Chandler *et al.*, 2001). The wider the row spacing, the higher the weed seed rain. Chandler *et al.* (2001) found greater weed seed return in soybean if the row spacing was 76 cm instead of either 38 or 19 cm (twin rows). Although the CWFP was similar across locations and years, CTWR varied among locations and between years in soybean (Van Acker *et al.*, 1993). The alternate wetting and drying in wet DSR favoured several flushes of weeds and extended CPWC (Raj and Syriac, 2017) beyond the CPWC duration limit. Variations in CPWC for rice under varied growing ecologies are presented in Table 3. For example, Johnson *et al.* (2004) noticed a CPWC of 4–83 DAS for the dry season lowland rice while only 29–32 DAS for the wet season lowland rice, underpinning that water regime as the chief determining factor of CPWC.

Further, CPWC has grossly ignored nutrient management, particularly the basal application of nutrients to crops. There are two probable situations under rainfed farming. First, a pre-emergence herbicide is ineffective due to either a lack of moisture or excess moisture after sowing under rainfed farming which when applied to the soil requires incorporation by rainfall, irrigation, tillage, etc. (Khalil *et al.*, 2019). Inthaphan and Thanomsak (1980) observed a complete loss of effectiveness of applying the herbicide to a dry rice seedbed if rains fail within 3–4 days of application. Second, post-emergence herbicides are applied around 20 DAS or slated for manual weeding around the end of CPWC. By that time, most of the soil-applied nutrients might have been extracted by the associated weed species.

Table 3. Variation in the critical period of weed control (CPWC) for rice under varied growing ecologies

Rice ecology	CPWC	Reference
Low land	29–32 DAS (wet season) 4–83 DAS (dry season)	Johnson *et al.* (2004)
	28–49 DAT (transplanted)	Mukhejee *et al.* (2005)
	20–40 DAT (transplanted)	Mukherjee *et al.* (2008)
Flood-irrigated	14–28 DAS	Begum *et al.* (2008)
Aerobic	18–52 DAS	Chauhan and Johnson (2011)
Upland	15–45 DAS	Singh *et al.* (1987)
Direct-seeded	16–53 DAS	Azmi *et al.* (2007*a*, 2007*b*)
	15–60 DAS	Mukherjee *et al.* (2008)
	28–42 DAS	Tagour *et al.* (2010)
	12–60 DAS	Azim *et al.* (2007*a*)
	2–71 DAS (saturated) 15–73 DAS (flooded conditions)	Juraimi *et al.* (2009)

DAS, days after sowing; DAT, days after transplanting.

Particularly under rainfed cultivation, farmers either skip the basal application of fertilizers or resort to weeding at the end of CPWC. Even if applied, herbicides can be exhausted by weeds or lost in the soil–plant–atmosphere system before the next weeding. Therefore, understanding the influence of nutrient management on CPWC (Knezevic *et al.*, 2002) warrants further investigations.

In conservation agriculture systems, rotations of crops inhibit the buildup of weed seedbanks (Kassam *et al.*, 2009; Kassam and Friedrich, 2011); however, non-selective, non-residual herbicides, such as glyphosate and paraquat, are used for weed management before sowing a crop (Beckie *et al.*, 2020) but they kill only emerged weed seedlings and have no effect on the weed seed bank. The interaction of weed–crop system becomes too complex under conservation agriculture (Ramesh, 2015). The seeds from the weed seed bank would still germinate and compete with the crop. Wherever pre-emergence herbicides are used for killing a wide range of weed species, some species would remain unaffected, and the escaped weeds enrich the soil's weed seed bank (Singh, 2008), or herbicide use in each cropping sequence would produce a shift in the weed seed bank in favour of species less susceptible to applied herbicides (Ball, 1992). In the perturbed agricultural ecosystem, where only a single species is allowed to perpetuate, certain weeds would naturally become adapted to exclusion mechanisms and survive and reproduce even in the presence of herbicides. Non-selective herbicides employed in herbicide-tolerant crops destroy the total weedy vegetation. Broad-spectrum post-emergence herbicides with an extended period of weed control (up to 20 days after application) may not prevent the germination of weed seeds. As a result, weeds that emerge in the later stage of the crop (i.e. after the end of the CPWC) may cause damage to the system as a whole. The normal and predictable outcome of natural selection expressed as herbicide resistance (Heap, 2013) and the herbicide-resistant weeds (Sosnoskie and Culpepper, 2014) would add to the weed seed bank.

Weed seed bank

A final factor promoting greater attention is the weed seed bank. One among the chief omissions of the CPWC concept is the weed seed rain from the escaped weeds and the damage to the succeeding crop barring the standing crop productivity. Inevitably, leaving weed seed banks in the CPWC will sooner or later derail the concept of CPWC. For long-term weed management, in addition to the recommended pre-emergence and post-emergence herbicides, either one additional post-emergence herbicide might be required, as suggested by Martin *et al.* (2001), or the weeds should be manually removed. Though the escaped weeds do not cause a significant yield loss in the standing crop, it increases the chance of higher weed infestation in the next season (Shrestha, 2004). For example, allowing late-emerging *E. colona* and *E. crus-galli* plants (45 days after rice emergence) to produce even a few seeds may cause these weeds to be an increasing problem in the subsequent seasons through seed rains to the soil seed bank (Chauhan and Johnson, 2010; Bagavathiannan *et al.*, 2012). Knezevic and Datta (2015) revisited the data analysis for CPWC, but the weed seed bank remained unaccounted for.

Mechanical weed management and CPWC

Most of the CPWC studies are based on manual/mechanical removal of weeds, not herbicide-based weed removal. Manual removal of weeds does facilitate soil aeration, and thus the yield obtained includes the confounding effects of weed removal and improved physical soil conditions as it appears that repeated tillage creates an environment conducive for better plant establishment (Workayehu, 2010). Ma *et al.* (2008) found that root pruning in wheat restrained transpiration of wheat and reduced the consumption of soil water in the early growing stages whereas at later stages, it enhanced the photosynthetic rate, partitioning of more photosynthates to the shoots, and increased harvest index. Root pruning reduced the number of spikes in wheat but increased the grain yield per spike and the 1000-kernel weight (Fang *et al.*, 2010). It is well-known that these effects are inseparable in the absence of herbicidal weed management, and the physical soil conditions have a significant positive effect on crop productivity. The process also involves root pruning, which is a beneficial practice in some crops for improved productivity through rapid reductions in stomatal conductance, for example, in sugarcane (Meinzer and Grantz, 1990) through the stomatal adjustment to the ratio of root hydraulic conductance to transpiring leaf area. In short, mechanical weed management carried out for CPWC studies may probably enhance the yield of the crops over unweeded or herbicide-applied crops.

General discussion and research needs

Although the concept of CPWC is a rule applied to several crops, it is not relevant to all field crops. For example, (i) initial slow growth in potato (Eberlein *et al.*, 1997) and pigeon pea may reduce their ability to compete with weeds and only the CTWR is meaningful and not the CPWC, and (ii) perennial weeds may not fall under the CPWC umbrella (e.g. NT systems) (Wrucke and Arnold, 1985). In these crops, weeds grow taller than the crop species. How certain can we be that the CWFP is relevant in these crops or that the effect of CPWC really pertains to yield loss? It seems to be a biased estimate indeed. CPWC is just as descriptive as observed by Weaver and Tan (1987) or

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CTWR should be synonymous with CPWC (Weaver and Tan, 1983) since CTWR is a relatively fixed estimate of the CWFP which has temporal variations (Karimmojeni *et al.*, 2014). van Heemst (1985) has opined that the onset of the sensitive period is generally not very critical, however, the end of the critical period is. In some cases, the onset of the CTWR itself varied between tillage systems, as well as within them, in glyphosate-tolerant soybean (Mulugeta and Boerboom, 2000). CPWC would likely be meaningful only if weed seed rain to the weed seed bank is also considered. There are various issues in CPWC for crops and/or the associated weed flora. Even if we could pose some answers for the CPWC, there remains one basic underlying assumption that during the CPWC, the field may remain weed-free either at CTWR or CWFP. There must be significant differences for the weed-free crop at the start and end of CPWC, which is not addressed by the CPWC. It is clear, therefore, that under the above observations, the CTWR seems to be more meaningful than the CPWC. It might be suggested, however, that, CPWC should focus on the weed seed bank and weed seedling recruitment so that the CPWC concept covers the whole spectrum of issues. The CPWC concept should encompass growing degree days (Stagnari and Pisante, 2011; Anwar *et al.*, 2012), plant ecological concepts and weed seed banks towards an improved and more integrated understanding of CPWC across all crops. The need to establish diverse approaches that can relate weed biology studies to practical weed management is endorsed by Chauhan *et al.* (2017). Although delineating CTWR for a crop in consonance with growing conditions may appear a herculean task with several experiments, these are needed to get meaningful and practical recommendations for minimizing weed competition in crops. Differences between seasons for the beginning and the end of the CPWC result in a change in weed densities (Tursun *et al.*, 2007) that reinforces the need for a review of CPWC. A more comprehensive methodology to calculate the CPWC needs to be devised considering the following aspects viz., cultivation seasons, genotypes, weed seed banks, rainfed/irrigated conditions, late-emerging weeds, dormant vegetative propagules, perennial weed density, conservation agriculture systems, slow-growing crops, weed specific CPWC, etc.

Conclusions

Despite continued research efforts and the knowledge generated on CPWC, it is still a developing science. CPWC is highly variable depending on the crops, growing conditions, seasons, weed seed banks and management practices followed by the farmers. In low-input farming systems, where herbicides are not used, the concept of CPWC can be misleading and should be avoided. It is concluded that CTWR is more meaningful than the CPWC.

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