# Review: The recruitment biology and ecology of large and small crabgrass in turfgrass: Implications for management in the context of a cosmetic pesticide ban

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This is an Accepted Manuscript of an article published by Canadian Science Publishing in the Canadian Journal of Plant Science on September 2012, available online: https://doi.org/10.4141/cjps2011-258

**Suggested Citation**: Turner, Fawn A., Jordan, Katerina S., and Van Acker, Rene C. (2012), Review: The recruitment biology and ecology of large and small crabgrass in turfgrass: Implications for management in the context of a cosmetic pesticide ban. Canadian Journal of Plant Science, 92(5): 829-845. https://doi.org/10.4141/cjps2011-258

# Review: The recruitment biology and ecology of large and small crabgrass in turfgrass: Implications for management in the context of a cosmetic pesticide ban

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**Abstract**: Large and small crabgrass (*Digitaria sanguinalis* and *Digitaria ischaemum*, respectively) are problem weeds within turfgrass. As seedling recruitment shapes the demography of annual weeds, it is important to assess the recruitment biology and ecology of crabgrass species to determine how these aspects may be impacted by various management techniques. This, in addition to an assessment of large and small crabgrass' response to cultural management techniques in turfgrass, is the objective of this review. Turfgrass management either directly or indirectly affects the crabgrass recruitment microclimate by impacting the soil, topography, resources or plant cover, which in turn affects the degree and timing of crabgrass recruitment. Due to the increasing number and scale of cosmetic use pesticide bans in Canada this topic is particularly relevant. Crabgrass experiences a dormancy period of several weeks prior to being able to germinate. Microsite conditions of temperature and moisture have the greatest influence on dormancy breaking and germination; however, other factors such as light have shown some effect on recruitment. There is also evidence that factors such as seed scarification or treatment with nitrogenous compounds can increase recruitment. In turfgrass, common cultural practices, such as mowing, irrigation, and fertilization, can affect the recruitment of crabgrass. By pairing knowledge of the effects of microsite conditions on crabgrass recruitment with management that favours turfgrass vigour, better management practices to deter crabgrass infestation can be recommended. There are large gaps in research pertaining to the effects of cultural management techniques on crabgrass recruitment. Research to date has failed to make critical links between knowledge of these species' recruitment biology and ecology and how this is affected or can be applied through herbicide alternative management. This review recommends that regional assessments of crabgrass populations are necessary to determine the most appropriate management strategies. This type of research would have the potential to guide ideal application timings for existing and developing alternative herbicides as well as recommendations for the best cultural management practices to deter crabgrass infestation in turf.

**Keywords**: Crabgrass (large and small), weed recruitment, turfgrass, pesticide ban, weed management

**Abbreviations**: CGM, corn gluten meal; CGH, gluten hydrolysate

Large [*Digitaria sanguinalis* (L.) Scop.] and small crabgrass [*Digitaria ischaemum* (Schreb.) ex Muhl.] are common weeds of most temperate and tropical regions throughout the world (Mitich 1988). With high fecundity, rapid growth, and relatively high tolerance to heat and drought, these species can often outcompete domestic turfgrasses. Traditionally, herbicides have been successful for controlling crabgrass populations. However in recent years, there have been restrictions placed on the use of turfgrass herbicides for cosmetic purposes. In Canada this includes Quebec in 2006 (Government of Quebec 2011), followed by Ontario in 2009 [Ministry of the Environment 2009] and subsequently New Brunswick (Government of New Brunswick 2009), Prince Edward Island (Government of Prince Edward Island 2011) and most recently Nova Scotia in 2011 (Government of Nova Scotia 2011). Pesticide restrictions dot municipalities throughout the remainder of the country, and western provinces continue to debate the issue of provincial regulations (Canadian Centre for Policy Alternatives SK 2007; British Columbia Ministry of Environment 2009; Government of Alberta 2010; Manitoba Round Table for Sustainable Development 2011). Consequently, in turfgrass systems there is a need to devise better cultural methods for crabgrass management proactively in the absence of herbicides. Better cultural management requires a better understanding of the biology and ecology of crabgrass (Van Acker 2009). The biology and ecology of crabgrass have been studied to a considerable extent but primarily in field crop scenarios in the United States. In Canada, the recruitment biology and ecology of crabgrass in turfgrass scenarios have been studied to only a very limited extent. The purpose of this paper is to provide a review of what is known about the recruitment biology and ecology of crabgrass, especially in the context of managed turfgrass, and to assess where substantive gaps in knowledge remain, especially in relation to crabgrass management.

Crabgrass (*Digitaria* spp.) is a monocotyledonous erect, or more commonly prostrate, summer annual grass propagated by seeds that are arranged closely on one side of flattened finger-like spikes (Mitich 1988; King and Oliver 1994; Royer and Dickinson 1999; Ontario Weeds 2010a, b). It can root at its nodes (Peters and Dunn 1971; Royer and Dickinson 1999; Ontario Weeds 2010a, b) and form thick mats in moist soil (Mitich 1988; Cudney and Elmore 2000). Crabgrass roots are fibrous and can extend up to 2 m in soil (Royer and Dickinson 1999), helping these species to survive droughty conditions.

Previous reports on the genus claimed that *Digitaria* was comprised of about 60 species, 13 of which were commonly found in the United States. (Mitich 1988). However, with the addition of newly described species and a broader consideration of the genus, more recent reports claim that 200 species comprise the genus with 29 species occurring in North America (Wipff 2003). In Canada, only three species are reported to exist, with the two most common species both here and in the United States being *Digitaria sanguinalis* (L.) Scop. and *Digitaria ischaemum* (Schreb.) ex Muhl., commonly called large or hairy and small or smooth crabgrass, respectively (Peters and Dunn 1971; Mitich 1988; Royer and Dickinson 1999; Wipff 2003; Ontario Weeds 2010a, b). These two species were first described in Europe in 1772 and 1804, respectively (Mitich 1988). Large crabgrass was brought into the United States in 1849 as a forage crop and was reintroduced by European immigrants as a grain crop around the turn of the 20th century (Foy et al. 1983). In Canada, large and small crabgrass incidence was first reported in 1845 (in Essex County, Ontario) and 1860 (in Prescott, Ontario), respectively (Dore and McNeill 1980). Large crabgrass has larger stems, leaves, inflorescences and seeds than small crabgrass, and also grows more upright (Peters 1964; Peters and Dunn 1971; Ontario Weeds 2010a; Weeds 2010b). The difference in size between these two species originates from the length of internodal stem space rather than a difference in the number of tillers produced (Peters 1964). While hairs are present in both species at the base of the leaf blades (Royer and Dickinson 1999), large crabgrass has pubescence on its sheaths, while mature small crabgrass generally lacks this characteristic (Peters 1964; Bouchard et al. 1999; Royer and Dickinson 1999). Although primarily hairless, small crabgrass may display pubescence in its seedling stage, with loose hairs up until the third or fourth leaf stage and may retain some hairiness usually on the underside of its leaf into its adult stages (Bouchard et al. 1999; Cudney and Elmore 2000). After the fourth leaf stage, both species sprout multiple tillers (Peters 1964). Peters and Dunn (1971) noted that with a sprawling growth habit and considerable tillering capacity, as few as two to three plants per 91 $cm^2$ area have the capacity to form complete ground cover within a season.

## *D. Sanguinals* and *D. Ischaemum* as weeds in turfgrass

Crabgrass is a problematic weed in a variety of ecosystems in Canada and it is considered a serious weed in row crops, cultivated fields, and turfgrass (Royer and Dickinson 1999). Crabgrass has been documented as a weed in every province in Canada except Saskatchewan and Newfoundland (Royer and Dickinson 1999) and both large and small crabgrass are considered common weeds in southern Ontario (Royer and Dickinson 1999; Ontario Weeds 2010a, b).

Crabgrass has been described as one of the most common and competitive weeds in managed turfgrass worldwide (Bhowmik 1987; Dernoeden et al. 1993; Kim et al. 2002; Hoyle et al. 2008; Melichar et al. 2008). Crabgrass not only competes with turfgrasses for moisture, light and nutrients, it also affects turf uniformity (Masin et al. 2006). Uniformity is an important aesthetic quality and it is functionally important for playing fields. In terms of management, specialty turf (e.g., used for commercial sports, including golf) is currently exempt from the Ontario pesticide ban, as are athletic fields used to host national or international competitions (Ministry of the Environment 2009). Crabgrass is a successful weed in turfgrass in part because of its comparatively rapid growth, which can crowd out other typically fine-leaved grass species and cultivars grown for turf (Mitich 1988). In addition, crabgrass can tolerate hot, dry summer conditions better than typical cool-season turfgrass species (Danneberger 1993; King and Oliver 1994). This may be in part because crabgrasses are C4 species, which enable them to use resources such as water and nitrogen more efficiently, and achieve higher maximum dry-matter yields compared with C3 species (Long 1983; Danneberger 1993), such as cool-season turfgrasses typically used in Canadian lawns. In China, for example, Wang et al. (2005) reported that small crabgrass sustained the lowest soil water content before unrecoverable wilting occurred when compared with Kentucky bluegrass (*Poa pratensis* L.) and five other common weeds (*Viola prionantha* Bunge, *Geranium sibiricum* L., *Potentilla anserina* L., *Inula britanica* L. and *Potentilla supina* L.). Crabgrass is particularly competitive in turfgrass that is stressed, as Richmond et al. (2003) demonstrated with perennial ryegrass (*Lolium perenne* L.) infected with the fungal endophyte *Neotyphodium lolii*. Crabgrass has also been shown to tolerate a wider pH range than many other species once established (Gilbert and Pember 1935; Buchanan et al. 1975; Pierce et al. 1999). However, Pierce et al. (1999) found that when soil pH was raised from 4.8 to 7.8 (via the addition of MgCO3) large crabgrass seed germination levels decreased. When the pH was raised using $CaCO_3$, however, germination levels were unaffected and when exchangeable Ca was increased alone using $CaSO_4$, there was also no effect on germination levels suggesting that Ca has a buffering effect on the impact of high pH levels on large crabgrass germination. Being aware of these differences may allow turfgrass managers to be prepared for potential crabgrass infestation when amending soil pH.

Turfgrass is often heavily trafficked or used recreationally and may therefore suffer the effects of compaction and wear. Although a hardened soil crust can decrease the emergence of crabgrass in some cases (Mohler and Calloway 1992), as a compaction-adapted weed, crabgrass is generally more tolerant of compaction than are many turfgrass species (Harivandi 2002). Gaps in turf created by compaction or wear create an opportunity for weed species to recruit and may lead to increased crabgrass infestation in areas affected by compaction or wear (Cudney and Elmore 2000). Traffic on turf may also help to break seed dormancy and move seeds to more favourable recruitment microsites (Feldman et al. 1997). In some situations, traffic may be advantageous to weeds in turf, including crabgrass.

Crabgrass is an annual weed and as such its success in turf is in great part a function of its ability to establish from year to year. Turfgrass management, such as fertilization, irrigation, mowing, aeration, and raking each affect the crabgrass recruitment microclimate either directly by seed movement or the distribution of resources, or indirectly by the degree of turfgrass cover and competition. Understanding crabgrass in the context of trying to better manage it in a turfgrass system will therefore require a good understanding of its recruitment biology and ecology and the conditions that provide or discourage recruitment and establishment opportunities. While it is, of course, possible to prescribe turfgrass management and surmise how this may affect crabgrass post hoc, the logical and scientific approach would be to determine how management strategies can affect crabgrass' biology and recommend management which targets recruitment.

## The recruitment biology and ecology of crabgrass

Recruitment is the ability for a seed to successfully germinate and emerge into an environment where it then has the potential to establish and replenish the seedbank (Harper 1977). This depends on several factors including seed persistence in the soil, dormancy status, the ability to germinate, and the ability of seedlings to grow towards the soil surface (Garadin et al. 2010). As the first process in the life cycle of annual weeds, seedling recruitment functionally shapes all subsequent demographics of a species (Leguizamon et al. 2008). Consequently, understanding weed biology and its relationship to management is a valuable resource for employing practical solutions in the field (Cici and Van Acker 2009; Van Acker 2009). This is particularly true in scenarios where one must rely primarily or exclusively on cultural management strategies to maintain crabgrass-free turf stands, as is the case in jurisdictions where there are cosmetic pesticide bans. In these cases, turfgrass management needs to focus to a substantive extent on the recruitment of crabgrass and knowledge of crabgrass recruitment biology and ecology will, therefore, aid the development of effective management.

The seedling recruitment microsite refers to the collective biotic and abiotic conditions surrounding seeds that affect seedling recruitment (Dyer 1995; Grundy et al. 1996). Soil temperature, moisture and light are often the most influential microsite characteristics (Harper 1977). Although not directly a microsite condition, seed burial is often a key influence on other microsite factors including temperature, moisture and light (Van Acker et al. 2004; Reid and Van Acker 2005). Total seedling recruitment, however, depends not only on adequate microsite conditions, but also on plant fecundity (quantity of seed rain) and seed longevity (Van Acker 2009). Together, these elements shape seedbank dynamics. Seedbanks may be depleted over time by germination or seed mortality and will persist as long as there is a replenishing source of seed (Baker 1989). Characterization of seedbank dynamics is important for understanding both a weed's impact on community ecology and the development of sustainable management strategies (Hill et al. 2001).

## Fecundity

Species fecundity can be used to estimate infestation potential (Van Acker 2009). However, estimates of seed rain and soil seedbank densities alone have proven insufficient for predicting crabgrass recruitment levels (Webster et al. 2003). Ultimately, it is population dormancy status and microsite conditions that determine whether seedlings will be recruited. However, the probability of recruitment increases as more seed is contributed to the soil (Boyd and Van Acker 2004).

Crabgrass is fecund and may produce up to 150 000 seeds per plant under ideal growing conditions (Mitich 1988; Royer and Dickinson 1999). Peters and Dunn (1971) reported that large crabgrass produced 145 000 to 154 000 seeds per plant at a spacing of 91 cm without competition from other species. They also reported that small crabgrass produced 188 000 to 210 000 seeds per plant at similar plant densities. In contrast, Aguyoh and Masiunas (2003) reported that small crabgrass seeded at 0.5 and 8 plants $m^{-2}$ produced only 3160 and 909 seeds per plant, respectively, although they did not account for shattered seed. In situ reports of crabgrass fecundity in turf scenarios do not exist and there is limited information on the ranges of crabgrass seed production under various conditions, or how seed production is affected by management strategies. Competition from surrounding plants (Peters and Dunn 1971; Crawley and Ross 1990) and time of emergence (Aguyoh and Masiunas 2003; Cici and

Van Acker 2009) can greatly reduce the overall fecundity. This is a testament to the virtue of maintaining the health and density of a turf stand in order to reduce opportunities for future infestation.

While crabgrass has high seed production, its prostrate architecture and the barochorous nature of its seeds limit seed dispersal. Consequently, if initial management fails to eliminate crabgrass prior to seed shed, observations of its distribution can provide a good indication of recruitment potential in the following season. In addition, seed predation can reduce the number of viable seeds among seasons. There are a variety of seed predators which may be responsible for the removal of weed seeds including invertebrates such as ground beetles, crickets, gastropods, millipedes and worms (Cardina et al. 1996; Carmona et al. 1999; Lundgren et al. 2005) and small vertebrates such as birds and rodents (Hulme 1994, 1998). Exclosure experiments in field crops have reported large crabgrass removal at a rate of 11% per day when only invertebrates were allowed access and approximately 13% when both invertebrates and vertebrates had access (Menalled et al. 1999). Lundgren et al. (2005) found granivorous arthropods consumed approximately 13% of crabgrass seeds per week. In non-agricultural ecosystems, seed predation may be buffered by recruitment from the seed bank and may not have as great an impact on weed recruitment (Crawley and Nachapong 1985), although this has not been specifically studied in turfgrass. Ground beetles, considered a major seed predator, were six times more abundant in a 10-yr-old cool-season turf stand than a newly established lawn (Rochefort et al. 2006). Seed predation experiments in unmanaged grasslands demonstrated that seed removal was greatest due to rodents and not to invertebrates (Hulme 1994). This suggests that seed predation may be high in some lawns, particularly well-established ones; however, the preferences of seed predators for turfgrass seed versus weed seeds such as crabgrass and whether this has a significant effect on crabgrass recruitment in turf has never been studied.

## Seed dormancy

Seed dormancy facilitates persistence and the success of annual weeds (Fenner 1995; Forcella 1998; Li and Foley 1997; Finch-Savage and Leubner-Metzger 2006). For large and small crabgrass, it appears that a combination of seed dormancy mechanisms can contribute to persistence. Both embryo immaturity when seeds are dispersed and coat imposed inhibition have been shown to contribute to dormancy maintenance (Hacker 1984). Large and small crabgrass seeds experience primary dormancy after shedding, and require a period of after-ripening before they are able to germinate (Toole and Toole 1941; Gianfagna and Pridham 1951; Peters and Dunn 1971; Taylorson and Brown 1977; Masin et al. 2006; Gallart et al. 2008). This means that turfgrass management techniques or products applied after seed is shed in late summer and early fall is applied to dormant seed. In cooler climates, like those in Canada, crabgrass seed germination is limited by cold temperatures after it has overcome dormancy.

Consequently, turfgrass treatments that are applied during this period of after-ripening may not be effective. Secondary dormancy has also been reported for large crabgrass when environmental requirements for germination are not met (Masin et al. 2006), but there has been no research conducted on how secondary dormancy in crabgrass may be affected by turfgrass management.

The time period to partial or complete after-ripening of large and small crabgrass has been documented in several studies (Table 1). Temperature at time of storage has a strong influence on dormancy status with prolonged dormancy observed at low temperatures (Table 1). Crabgrass seed stored in the dark at room temperature has been shown to overcome dormancy in 4 to 6 mo, and dormancy can be broken more quickly when seeds are exposed to high or alternating high and low (room) temperatures (Table 1). Additionally, chilling crabgrass seed will break dormancy (Baskin and Baskin 1988; Grundy 2003; Table 1). This indicates that crabgrass is able to germinate in late winter and early spring within this region and its recruitment is only limited by sufficient heat accumulation. Consequently, if temperatures early in the season were to increase, crabgrass emergence may occur earlier in the season. Crabgrass seed dormancy is substantively influenced by the caryopsis covering structures and seed coat (Gallart et al. 2008). Physical scarifying or de-hulling are effective for breaking the dormancy of large (Toole and Toole 1941; Martin 1943; Gianfagna and Pridham 1951; Delouche 1956; Gallart et al. 2008) and small (Toole and

Toole 1941) crabgrass seed. For example, rubbing intact spikelets with moist sand increased germinability by 30% (Gallart et al. 2008). In addition, removal of the glumes and the lemma of the sterile floret increased germination by 15%, whereas the removal of the lemma of the perfect floret increased germination by 75% (Gallart et al. 2008). Puncturing the pericarp and testa increased germination of large crabgrass by 84% and dehulling the caryopses with emery paper has been shown to be a very successful dormancy breaking treatment, increasing germination levels to 95% (Gallart et al. 2008). Therefore, management strategies that affect the structural integrity of crabgrass seed may result in an increase in crabgrass recruitment. Raking, or the traffic of machinery such as mowers or seed and fertilizer distributors could potentially lead to scarification or the removal of seed covering structures, although no one has ever investigated whether these management activities would actually impact recruitment and infestation levels. Chemical scarification has only proven partially successful for dormancy breaking for small crabgrass (Toole and Toole 1941), and has been unsuccessful for large crabgrass (Toole and Toole 1941; Gallart et al. 2008). Seed aging increases seed coat permeability and decreases the need for seed coat puncturing to enable germination, and this has been demonstrated for large crabgrass (Egley and Chandler 1978; Egley and Chandler 1983).

Table 1. Effects of time, temperature and storage conditions on seed dormancy in large and small crabgrass$^{z}$

| Days after seed shed$^{y}$ | Temperature (°C) | Storage$^{x}$ | Seed Origin | Germination | Citation |
|---|---|---|---|---|---|
| Large crabgrass | | | | | |
| 5 | 10 | Moist, light | N/A | PS | Delouche (1956) |
| 14$^{y}$ | 50 | Dry, dark$^{x}$ | MD | 33% | Taylorson and Brown (1977) |
| 14$^{y}$ | 50 | Dry, light$^{x}$ | MD | 94% | Taylorson and Brown (1977) |
| 30 | Room temp. | Dry, dark | Barcelona | 0% | Gallart et al. (2008) |
| 56 | 2-4°C | Moist, light | N/A | S | Delouche (1956) |
| 60 | Room temp. | Dry, dark | Barcelona | 4% | Gallart et al. (2008) |
| 60 | 15/25 (18 h/6 h) | Dry | WA | PS | Toole and Toole (1941) |
| 60 | 20/30 (18 h/6 h) | Dry | WA | PS | Toole and Toole (1941) |

| Days after seed shed[y] | Temperature (°C) | Storage[x] | Seed Origin | Germination | Citation |
|---|---|---|---|---|---|
| 60 | 20/40 (18 h/6 h) | Dry | WA | PS | Toole and Toole (1941) |
| 60-90 | 14 | Dry | N/A | PS | Martin (1943) |
| 60-90 | 20-23 | Dry, dark | MS | 73% | Egley and Chandler (1978) |
| 90-120[w] | 5 | Dry | NE | 6% | Burnside et al. (1981) |
| 90 | 20/30 (18 h/6 h) | Dry | WA | S | Toole and Toole (1941) |
| 90 | 20/35 (18 h/6 h) | Dry | WA | S | Toole and Toole (1941) |
| 120 | Room temp. | Dry, dark | Barcelona | >95% | Gallart et al. (2008) |
| 180 | 25 | Dry, dark | AL | S | Biswas et al. (1978) |
| 180 | 5 | Dry, dark | AL | 0% | Biswas et al. (1978) |
| NA | 15/30 (16 h/8 h) | N/A | N/A | PS | Delouche (1956) |
| Small crabgrass | | | | | |
| 14[y] | 50 | Dry, dark[x] | MD | 43% | Taylorson and Brown (1977) |
| 14[y] | 50 | Dry, light[x] | MD | 70% | Taylorson and Brown (1977) |
| 14-28 | 2-5 | Moist | WA | PS | Toole and Toole (1941) |
| 56 | 2-5 | Moist | WA | S | Toole and Toole (1941) |
| 60 | 15/25 (18 h/6 h) | Dry | WA | PS | Toole and Toole (1941) |
| 60 | 20/30 (18 h/6 h) | Dry | WA | PS | Toole and Toole (1941) |
| 60 | 20/35 (18 h/6 h) | Dry | WA | PS | Toole and Toole (1941) |
| 60 | 20/40 (18 h/6 h) | Dry | WA | PS | Toole and Toole (1941) |
| 150 | 20/35 (18 h/6 h) | Dry | WA | S | Toole and Toole (1941) |
| 150 | 20/40 (18 h/6 h) | Dry | WA | S | Toole and Toole (1941) |
| 365 | Room temp. | Dry | WA | S | Toole and Toole (1941) |

[z] Abbreviation: N/A, data not available; S, successful; PS, partially successful.
[y] Days after seed shed describes the storage time after which the temperature treatment was applied, unless denoted by "y", then temperature treatment commenced with fresh seed for the period specified.
[x] Storage describes the conditions which seed was maintained prior to temperature treatment, unless denoted by "x" prior to temperature treatment, then conditions describe those coinciding with temperature treatment. All other seed was stored at room temperature.
[w] Tetrazolium chloride viable seed=88%.

Moisture can influence crabgrass seed dormancy. Pre-soaking large crabgrass seed can break dormancy in some cases (Delouche 1956) and Gallart et al. (2008) confirmed this by pre-soaking fresh crabgrass spikelets for 4 d, resulting in a 20% increase in germination levels. Similarly, Taylorson and Brown (1977) found that after a 14-d period at 50°C, moisture loss from large crabgrass seed in unsealed vials resulted in 91% less seed becoming non-dormant in comparison to seeds in sealed vials. Soaking crabgrass seeds may also overcome low temperature dormancy (Table 1). From a management perspective, this favours the use of deep and infrequent irrigation to limit crabgrass seed germination, rather than consistent and light irrigation, which could maintain imbibition and increase recruitment levels.

Light also can influence crabgrass seed after-ripening, although the effects are variable (Toole and Toole 1941; Gianfagna and Pridham 1951). Taylorson and Brown (1977) noted that exposure to light increased the proportion of nondormant seed, and that there was a greater effect on large versus small crabgrass (Table 1). However, Toole and Toole (1941) reported that small crabgrass seed dormancy was unaffected by light. In general, the germination of large and small crabgrass seed will occur in either continuous light or dark when other conditions are not limiting (Peters and Dunn 1971; Cudney and Elmore 2000). However, light exclusion has been shown to retard the germination of large crabgrass (Toole and Toole 1941; Peters and Dunn 1971; Mohler and Calloway 1992), while no similar effect has been observed for small crabgrass (Toole and Toole 1941; Peters and Dunn 1971; Baskin and Baskin 1988). In practical terms, the degree of light intercepting crabgrass seed on the soil surface is largely influenced by the density of turfgrass cover, as well as the growth habit of the turf. For instance, stoloniferous turf species produce greater thatch and therefore provide greater shading than do rhizomatous or bunch-type grasses. In addition, turf height greatly influences the degree of shading provided and therefore mowing is another direct control of crabgrass seed light interception. In theory, these types of management approaches or turf types could play a role in limiting crabgrass recruitment, but these effects have never been explored in any sort of controlled studies.

Nutrients, such as nitrogen (N), can act to break seed dormancy. As fertilization is a commonly practiced cultural management in turfgrass, this may have a direct effect on crabgrass' recruitment biology. Gallart et al. (2008) treated intact spikelets of large crabgrass with potassium nitrate ($KNO_3$) 2 mo after harvest and found an increase in germination levels (12% versus 4% in water controls after a 15-d incubation period at 20/30°C in 12/12 h of light/dark, respectively). The effect of nitrogenous compounds on seed dormancy breaking in crabgrass can be more pronounced when combined with de-hulling (Delouche 1956; Gallart et al. 2008), although results from other experiments have been inconsistent (Toole and Toole 1941). $KNO_3$ (applied at 0.2%) has been shown to promote the rate of small crabgrass germination of previously dormant seed at temperature regimes of 15/25°C and 20/30°C, but it retarded germination at higher temperature regimes of 20/35°C or 20/40°C (18 h/6 h) (Toole and Toole 1941). Seed coats of large crabgrass have been shown to restrict oxygen uptake in dormant seeds (Biswas et al. 1978), increasing oxygen partial pressure to 100% has been shown to have no effect on crabgrass seed dormancy breaking or on germination levels (Gianfagna and Pridham 1951; Delouche 1956).

Other chemical treatments have also been shown to affect seed dormancy in crabgrass species including chlorohydrins (a group of rotenticides), 1,2-dibromo-3- chloropropane (a nematicide) and ethanol. Ethylene chlorohydrin (500 ppm) has been shown to break seed dormancy in large crabgrass after 48 h (Gianfagna and Pridham 1951) and there is some dormancy breaking when ethylene is pre-applied at 0.125 to 0.5% after 24 or 48 h (Delouche 1956). 1,2-Dibromo-3-chloropropane (10 ppm) partially breaks dormancy in large and small crabgrass (Miller et al. 1965). Similarly, ethanol (at a rate of $50x10^6L^1$) applied for 7 d provides some dormancy breaking for both large and small crabgrass seed (Taylorson and Hendricks 1973).

## Seed longevity

If conditions for breaking dormancy are not met, crabgrass seed may remain dormant yet viable for years in the soil (Peters and Dunn 1971; Table 2). One report has shown that a small proportion of crabgrass seed persisted for a decade (Table 2). This can make effective management more difficult as crabgrass infestation may occur in areas previously thought to be crabgrassfree. Like dormancy, the environment in which weed seeds mature (Dawson and Burns 1975; Masin et al. 2006; Cici and Van Acker 2009), or differences among genotypes (Masin et al. 2006) may result in seeds from the same species persisting for different lengths of time (Egley and Chandler 1978; Masin et al. 2006).

Substantive differences in longevity have been reported for crabgrass seed stored in dry conditions as compared with those buried in soil (Table 2). For example, nearly 100% of crabgrass seeds remained viable when stored in dry conditions for up to 5 yr (Comes et al. 1978; Egley and Chandler 1983), while complete viability of seed buried in soil may last for less than 6 mo (Egley and Chandler 1983; Masin et al. 2006). These studies are encouraging in terms of crabgrass management because they suggest this species has a relatively short-lived seed bank and if seed return can be severely limited then the population (including its seed bank) can be substantively reduced.

Table 2. Longevity of exhumed large and small crabgrass seed after burial or dry storage

| Months after seed shed | Storage or burial (cm) | Seed origin | Longevity[z] | Citation |
|---|---|---|---|---|
| *Large crabgrass* | | | | |
| 3 | 4 - 4.5[y] | Italy | 85 to 90% | Masin et al. (2006) |
| 3 to 4 | Dry-stored, 5°C | NE | 6%[z] | Burnside et al. (1981) |
| 6 | 8, 23, and 38[x] | MS | 83% | Egley and Chandler (1978) |
| 12 | 23 cm | NE | 12%[z] | Burnside et al. (1981) |
| 12 to 48 | 23 cm | NE | 3 to 4%[z] | Burnside et al. (1981) |
| 15 | 4 – 4.5[y] | Italy | 50% | Masin et al. (2006) |
| 18 | 8, 23, and 38[x] | MS | 30% | Egley and Chandler (1978) |
| 23 | 4 – 4.5[y] | Italy | <5% | Masin et al. (2006) |
| 30 | Dry-stored, 4°C | MS | 91% | Egley and Chandler (1978) |
| 30 | 8, 23, and 38[x] | MS | 13% | Egley and Chandler (1978) |
| 40 | 4 – 4.5[y] | Italy | <1% | Masin et al. (2006) |
| 42 | 8, 23, and 38[x] | MS | 0 to 1% | Egley and Chandler (1983) |
| 48 to 120 | 23 cm | NE | 1 to 4% | Burnside et al. (1981) |
| 54 | 8, 23, and 38[x] | MS | 0 to <1% | Egley and Chandler (1983) |
| 60 | Dry-stored, room temp. | WA | 97% | Comes et al. (1978) |
| 66 | Dry-stored | MS | 99% | Egley and Chandler (1983) |
| 66 | 8, 23, and 38[x] | MS | 0% | Egley and Chandler (1983) |
| *Small crabgrass* | | | | |
| 60 | Dry-stored, room temp. | WA | 99% | Comes et al. (1978) |

[z] Viability (total of independent germination, germination after seed coat piercing, and tetrazolium test, or resistance to forceps) unless denoted by "z" in which only germination of fresh seed is reported.
[y] Buried under permanent turf.
[x] Depth not significant.

## Germination and emergence

Germination is considered a separate step in the plant development process and, like after-ripening, there are species-specific environmental requirements for germination to occur (Baker 1989). This process is followed by emergence which requires shoot elongation to reach the surface, and radical elongation to ensure water and nutrient uptake (Durr and Aubertot 2000). The key to understanding the timing of seedling recruitment is understanding how the physical environment affects germination and emergence (Bullied et al. 2012). Soil temperature and water availability are the primary drivers of crabgrass germination and emergence (King and Oliver 1994; Masin et al. 2005). Therefore, by accounting for these factors through the assessment of contributing elements such as shading, shelter, ground cover, and soil type in turfgrass, a more accurate prediction of germination and emergence timing of crabgrass is possible. However, seeds of the same species may differ in their response to water stress (Masin et al. 2005) or temperature (Forcella et al. 2000) as an artefact of locally derived adaptation (Steinmaus et al. 2000). Consequently, a wide variation in emergence timing is not uncommon among locations (Table 3). Studying specific ecotypes of interest is therefore important for understanding germination and emergence (Steinmaus et al. 2000). In field crop scenarios, timing of crabgrass seedling emergence appears to coincide with the onset of increasing soil temperatures and decreasing soil water potential (Toole and Toole 1941; Peters and Dunn 1971; Gianfagna and Pridham 1951; King and Oliver 1994; Masin et al. 2005; Myers et al. 2005).

Although crabgrass can exhibit continuous emergence throughout the season (Cudney and Elmore 2000), peaks in emergence coincide with favourable environmental conditions (Table 3). In some cases, models have been developed to describe and predict the emergence of large (King and Oliver 1994; Masin 2005; Leguizamon et al. 2008) and small (Fidanza et al. 1996) crabgrass with some degree of accuracy. The effect of temperature on crabgrass germination (Table 4) and emergence (Table 5) has been well documented. Baskin and Baskin (1988) have shown that base germination temperatures for crabgrass may decrease as after-ripening progresses (Baskin and Baskin 1988). In turfgrass systems, crabgrass emergence can be delayed by a lag in soil warming, especially when compared with bare soil (Myers et al. 2005). Fidanza et al. (1996) showed that small crabgrass emerges a week later in turfgrass versus bare soil. Consequently crabgrass may emerge first in thin or open areas of turf, which warm up more quickly, or near heat sinks such as sidewalks (Cudney and Elmore 2000).

Water uptake occurs during three distinct phases of germination; seed imbibition, followed by a lag phase where there is little water uptake, and finally water uptake associated with growth leading to seedling emergence (King and Oliver 1994). Although Gianfagna and Pridham (1951) have shown that non-dormant seeds of large crabgrass take up more water in 24 h than dormant seed, Biswas et al. (1978) found that there is little difference between dormant and non-dormant seeds in this regard provided that there are no physical differences between the seed, such as removed or degraded hulls. Large crabgrass seed has been shown to germinate within 24 h of soaking in water and at 76 h it can produce green shoots and start chlorophyll synthesis (Biswas et al. 1978). As with temperature, percentage and rate of germination increase as available soil water increases above a base requirement until an optimum is attained (King and Oliver 1994; Feng et al. 2004). In many studies, moisture availability is not measured directly, but rather is represented by the frequency or overall quantity of precipitation or irrigation, making direct comparisons among studies difficult. However, crabgrass emergence generally coincides with increased water availability. For example, Peters and Dunn (1971) found that when soil moisture on bare soil patches was conserved by covering the soil with saran cloth there was significantly greater emergence of both large and small crabgrass. Alternatively, Comes et al. (1978) found that germination of large crabgrass was reduced by approximately 50% after 3 to 24 mo of complete submergence in fresh water, declining to 0% after 60 mo. The germination of small crabgrass was completely inhibited after only 3 mo of submergence.

Table 3. Emergence timing for large and small crabgrass[z]

| Location[xy] | Emergence Begins | Emergence Peaks | Emergence Ends | Citation |
|---|---|---|---|---|
| *Large crabgrass* | | | | |
| Italy[y] | Late Mar. to early Apr | Mid- to late May | Early Aug. to Sep. | Masin et al. (2005) |

| Location[xy] | Emergence Begins | Emergence Peaks | Emergence Ends | Citation |
|---|---|---|---|---|
| DE, NJ, PN | Mid- to late April | Mid-May and mid- to late June | Mid- to late Jul. | Masin et al. (2005) |
| CT | Mid- to late May | N/A | N/A | Peters and Dunn (1971) |
| NY | Late May | N/A | Mid-Sep. | Gianfagna and Pridham (1951) |
| OH[y]* | First: 211 GDD | 50%: 692 GDD | 80%: 1160 GDD | Cardina et al. (2011) |
| OH* | First: 306 GDD | 50%: 693 GDD | 80%: 1888 GDD | Cardina et al. (2011) |
| DE, NJ, PN** | 10%: 280 GDD | 50%: 580 GDD | 95%: 1500 GDD | Myers et al. (2004) |
| Argentina*** | 25%: 30-210 GDD | 50%: 80-280 GDD | 75%: 160-360 GDD | Leguizamon et al. (2008) |
| *Small grabgrass* | | | | |
| CT | Mid- to late May | N/A | N/A | Peters and Dunn (1971) |
| MD[y]**** | Late Apr to early May | 140 to 230 GDD | Early Sep. | Fidanza et al. (1996) |
| MD[y]**** | 25%: 310 GDD | 50%: 445 GDD | 75%: 945 GDD | Fidanza et al. (1996) |
| OH[y]* | First: 155 GDD | 50%: 354 GDD | 80%: 548 GDD | Cardina et al. (2011) |
| OH* | First: 178 GDD | 50%: 347 GDD | 80%: 448 GDD | Cardina et al. (2011) |

[z] Abbreviation: N/A, data not available; GDD, growing degree days.
[y] Observations made in crop systems unless denoted, then in turf.
[x] Counting of degree days begin in Jan, Tb10 (*); Jan, Tb9 (**); Apr, Tb13.6 (***); and Aug, Tb12 (****).

Table 4. The influence of temperature and water potential on non-dormant large and small crabgrass seed germination[z]

| Temperature (°C) | Soil water potential | Length (d) | Germination[y] | Seed origin[x] | Citation |
|---|---|---|---|---|---|
| *Large crabgrass* | | | | | |
| 8.4 +/- 1.07°C | -830 +/- 255 kPa | N/A | Base | Italy | Masin et al. (2005) |
| 15.1°C | N/A | N/A | Base | CA | Steinmaus et al. (2000) |
| 10 to 13°C | N/A | 3 | Yes | CA | Cudney and Elmore (2000) |
| 15°C | 0 kPa | 10 to 12 | 12% | MS | King and Oliver (1994) |
| 20/40°C (18 h/6 h) | N/A | 14 | Yes | WA | Toole and Toole (1941) |
| 20/35°C (18 h/6 h) | N/A | 14 | Yes | WA | Toole and Toole (1941) |
| 20/30°C (18 h/6 h) | N/A | 14 | Yes | WA | Toole and Toole (1941) |
| 15/25°C (18 h/6 h) | N/A | 14 | Yes | WA | Toole and Toole (1941) |
| 25°C | 0 to -200 kPa | 8 | 60% | MS | King and Oliver (1994) |
| *Small crabgrass* | | | | | |
| 30/15°C | N/A | N/A | Base[w] | N/A | Baskin and Baskin (1988) |
| < 30/15°C | N/A | N/A | Base[v] | N/A | Baskin and Baskin (1988) |
| 10 to 13°C | N/A | 3 | Yes | CA | Cudney and Elmore (2000) |

| Temperature (°C) | Soil water potential | Length (d) | Germination[y] | Seed origin[x] | Citation |
|---|---|---|---|---|---|
| 20/40°C (18 h/6 h) | N/A | 14 | Yes | WA | Toole and Toole (1941) |
| 20/35°C (18 h/6 h) | N/A | 14 | Yes | WA | Toole and Toole (1941) |
| 20/30°C (18 h/6 h) | N/A | 14 | Yes | WA | Toole and Toole (1941) |
| 15/25°C (18 h/6 h) | N/A | 14 | Yes | WA | Toole and Toole (1941) |

[z] Mature seed used for germination tests.
[y] Base: conditions at which germination first occurs.
[x] Abbreviation: N/A, data not available.
[w] Base temperature when seed first after-ripened.
[v] Base temperature with additional after-ripening.

Table 5. The influence of soil temperature and water potential on non-dormant large crabgrass seedling emergence[z]

| Soil temp (°C) | Soil water potential | Emergence | Seed origin | Citation |
|---|---|---|---|---|
| 5-10 | N/A | None | China | Feng et al. (2004) |
| <10 | N/A | None | Modelled | King and Oliver (1994) |
| N/A | -30 to -100 kPa | None | Modelled | King and Oliver (1994) |
| N/A | < -50 to -60 kPa | Little to none | MS | King and Oliver (1994) |
| N/A | -500 kPa | Base | Modelled | Forcella et al. (2000) |
| 9 | N/A | Base | DE, NJ, PN | Myers et al. (2004) |
| 12 | N/A | Base | Maryland | Fidanza et al. (1996) |
| <15 | N/A | Little to none | MS | King and Oliver (1994) |
| 15 | N/A | 9-10 DAP | Modelled | King and Oliver (1994) |
| 15-40 | | Yes | China | Feng et al. (2004) |
| 20-30 | 60% $\theta_m$ | Max. | China | Feng et al. (2004) |
| >22.8 avg. | N/A | Max. | MD | Fidanza et al. (1996) |
| 25 | -30 kPa | Max (77%) | Modelled | King and Oliver (1994) |
| 30-35 | N/A | 2 to 3 DAP | Modelled | King and Oliver (1994) |
| 40 | 20% $\theta_m$ | None | China | Feng et al. (2004) |

[z] Abbreviation: N/A, data not available; Base, conditions at which emergence first occurs; DAP, days after planting; Max., conditions at which maximum emergence occurs; $\theta_m$, gravimetric water content.

## Seed depth and emergence

Seed burial depth can influence microsite characteristics and place physical limitations on the ability of seeds to germinate or seedlings to emerge (du Croix Sissons et al. 2000; Van Acker et al. 2004; Reid and Van Acker 2005). To-date, recruitment experiments conducted by placing weed seeds at specific depths in the soil (Peters and Dunn 1971; Benvenuti et al. 2001; Garadin et al. 2010) have provided an estimation of the maximum emergence depth of crabgrass. No experiment to date has utilized natural weed seed banks to determine recruitment depth of crabgrass in situ. However, the tendency towards shallow seedling recruitment is typical among many common weed species (du Croix Sissons et al. 2000; Forcella et al. 2000), with the reduced movement of seeds in the soil profile of turfgrass resulting in the accumulation of weed seeds primarily within the first 4 cm beneath the thatch and roots (Baker 1989; Masin et al. 2006). Turfgrass management such as aeration, raking, or traffic from mowers or seed and fertilizer distributing machinery may affect the burial depth of crabgrass seed by either bringing seed to the surface or increasing vertical displacement.

Peters and Dunn (1971) reported that small crabgrass had twice the levels of emergence compared with large crabgrass when seeds were placed at shallow depths (less than 5 cm), while large crabgrass had a greater ability to emerge when seeds were placed at depths greater than 5 cm. This may be a function of differences in seed sizes, as large crabgrass seed has been reported to have a mean seed weight of 0.46 to 0.67 mg (Benvenuti et al. 2001; Garadin et al. 2010) and small crabgrass seed has a mean seed weight of 0.59 mg (Terpstra 1986). Feng et al. (2004) found that large crabgrass emergence percentages were highest for seed placed at a depth of 2 to 3 cm while in the study by Peters and Dunn (1971), the effect of burial on emergence levels was minimal for seed placement depths of up to 5.08 cm and 3.81 cm for large and small crabgrass, respectively. Peters and Dunn (1971) reported the maximum depth of emergence for large and small crabgrass as 7.62 and 5.35 cm, respectively. Benevenuti et al. (2001) reported the maximum depth of emergence for large crabgrass biotypes from Italy to be only 6 cm. They also reported that large crabgrass emergence was reduced by 50% at a seeding depth of 4.1 cm. In France, Garadin et al. (2010) estimated the maximum shoot length of large crabgrass to be approximately 3 cm (at a base temperature of 8.4°C), and rationalized that this would correspond to the maximum possible depth of emergence. In general, emergence levels of both large and small crabgrass decrease with increasing depth of seeding, while time to emergence increases. At depths below which no large crabgrass seed emerged, Benvenuti et al. (2001) found that approximately 85% of the remaining seed was dormant. This suggests that if seed were brought to the surface, via core aeration for example, crabgrass seed germination may increase, leading to infestation.

Being prepared to manage newly recruited weed seedlings at this time is an important management strategy, particularly, late in the season when lawns are often stressed and vulnerable to invasion. By understanding the depth of crabgrass seed burial, recruitment timing may also be more accurately predicted. Benvenuti et al. (2001) demonstrated this for large crabgrass where any increase of seeding depth of 2 cm or more significantly increased time to emergence. Therefore, knowledge of crabgrass seed burial in turf stands can be an aid to effective management application and timing.

Soil texture can influence both seedling emergence and seed longevity (Bewley and Black 1985). With increasing size of soil particles, large crabgrass seedling mortality has been predicted to increase according to model simulations (Garadin et al. 2010). At a 1-cm depth of burial, for example, seedling mortality was predicted to increase by 22 and 37% in fine- and coarse-textured soil, respectively. In turfgrass, burial beyond the first few centimetres of soil may occur when using mechanical cultivation techniques. The effect of soil texture on crabgrass recruitment has never been studied directly, but the effect of soil clods on crabgrass emergence has been studied. Using pre-germinated seeds buried to a depth of 2 cm, Garadin et al. (2010) found that the percentage of seedlings blocked from emerging increases as clod size on the soil surface increases (40 to 70%). Clods are even more effective at inhibiting emergence when they are buried under a layer of fine-textured soil (65 to 90%) (Garadin et al. 2010). Compared with 12 other weeds, the emergence of large crabgrass is more frequently blocked by clods and Garadin et al. (2010) suggested that this was because large crabgrass has a smaller shoot diameter (0.41 +/- 0.06 mm) and fewer stored reserves (as a monocot) compared with many other weed species. Greater seed weight has been correlated with greater potential depth of emergence (Van Acker et al. 2004) and this has been observed for large crabgrass (Benvenuti et al. 2001). This may also point to seed stores as a limiting factor in determining the maximum depth of emergence or emergence capability when there is physical impedance. In another study, the germination of small crabgrass was shown to be unaffected by increasing clod size on the soil surface (with diameters of 1.5 to 5.3 cm) or hardness of clods (with soft and hard clods having a dry bulk density of 1500 or 1750 kg $m^{-3}$ , respectively) (Terpstra 1986). Contrasting conclusions may be because Terpstra (1986) did not bury seeds below the surface or increase clod size as greatly as did Garadin et al. (2010). The ability of pre-germinated seeds of small crabgrass to emerge against soil clods or the effect of soil clods on the germination of large crabgrass has not been studied nor has the purposeful structuring of turf substrates to reduce weed recruitment. While not all of these factors can be affected via management techniques, approaches such as amending soil or the degree of compaction can be managed. While some factors such as increased soil clods have been shown to have a negative effect on the recruitment of crabgrass, they may ultimately have a greater negative impact on the recruitment of the turfgrass species. Furthermore, while crabgrass recruitment is negatively affected by compaction, it is better able to recruit in compacted soils than many typical turfgrass species, and this is an important consideration when establishing lawns from seed, especially later in the season (Mohler and Calloway 1992; Harivandi 2002).

## Management of crabgrass in turf without conventional pesticides

Management practices in turfgrass systems may favour or disfavour crabgrass recruitment and establishment. Crabgrass is capable of recruiting from a wide variety of microsites, which makes it a problematic summer annual weed. However, crabgrass favours high temperatures and open areas of turfgrass, which allow greater light interception. Although crabgrass requires moisture for germination, it is robust in its ability to establish despite drought-like conditions. Traditionally, the application of conventional herbicides has been popular as an efficient, simple and relatively successful method of achieving crabgrass control. In light of the movement away from synthetic pesticide use, evidenced by bans in numerous regions, there is increasing and sometimes urgent interest in the use of alternative control and management methods for crabgrass, including the use of bioherbicides. Cultural weed management techniques in turfgrass often target the improvement of turf vigour in an attempt to reduce opportunities for and the success of weed recruitment and establishment (Cudney and Elmore 2000; Busey 2003). However, as weeds are often a consequence of improper site preparation or management (Masin et al. 2005), if techniques are not employed properly or at the appropriate time, crabgrass may establish ahead of new turf and have a competitive advantage. Mowing, irrigation and fertilizer practices can each work for or against the establishment and maintenance of healthy, crabgrass-free turfgrass.

## Knowledge of recruitment biology and ecology and crabgrass management

Mowing is perhaps the most common cultural management practice in turfgrass systems and mowing height can affect the success of crabgrass populations in turf. Generally, lower mowing height results in increased crabgrass density in residential turf, whereas mowing at heights of 4 to 8 cm can act to reduce crabgrass populations (Busey 2003). This effect may be related to limits on opportunities for seedling recruitment and growth due to reduced light interception (Toole and Toole 1941; Gianfagna and Pridham 1951; Taylorson and Brown 1977). Voigt et al. (2001) found that unfertilized tall fescue [*Schedonorus phoenix* (Scop.) Holub] maintained at 5.2 cm and 7.6 cm had significantly less crabgrass cover than plots maintained at 2.5 cm. Similar results have been reported in other studies on tall fescue (Dernoeden et al. 1993; Hoyle et al. 2008), red fescue (*Festuca rubra* L.) (Jagschitz and Ebdon 1985) and Kentucky bluegrass (Niehaus 1974 as cited in Busey 2003; Dunn et al. 1981 as cited in Busey 2003, 1981; Fidanza et al. 1996). This may help, in part, to explain why crabgrass is found more often (at least initially) around lawn edges or next to obstructing fixtures such as sprinkler heads, where mowing height is typically lower (Cudney and Elmore 2000). In some cases, the relatively prostrate growth habit of crabgrass may allow it to avoid being mowed (Mitich 1988). Additionally, Cudney and Elmore (2000) found that smaller crabgrass plants could tolerate mowing heights as low as 6 mm and still flower and produce seed (Cudney and Elmore 2000).

Over-seeding turfgrass where thin or bare areas exist can minimize the risk of crabgrass infestation, although timing of seed application often affects the success of this practice (Cudney and Elmore 2000). For example, in a Californian study, complete control of large and small crabgrass was achieved with fall seeding, while control was variable with spring seeding (Cudney and Elmore 2000). Seed laid in the fall may have had the opportunity to establish earlier than seed laid in the spring and therefore could better compete against weed infestation.

It is a recommended practice in turfgrass systems to apply fertilizer only when the turfgrass is actively growing in order to avoid favouring weeds (Cudney and Elmore 2000; Busey 2003). In field crop experiments, N applications ranging from 300 to 375 kg actual N $ha^{-1}$ did not affect large crabgrass dry weight (Abouziena et al. 2007), and Swanton et al. (1999) found that N applications at rates of up to 200 kg actual N $ha^{-1}$ did not affect large crabgrass densities. It has, however, been shown that timely applications of higher rates of N can reduce crabgrass populations in swards of Kentucky bluegrass (Dunn et al. 1981 as cited in Busey 2003; Johnson and Bowyer 1982; Murray et al. 1983), tall fescue (Dernoeden et al. 1993; Voigt et al. 2001), and red fescue (Jagschitz and Ebdon 1985), even in the absence of herbicides in some cases. Similarly, Hall (1977) showed that fall versus spring applications of N reduced the invasive success of small crabgrass in turfgrass maintained at a height of 2.5 cm. Fall-applied fertilizer may favour cool season and early emerging turfgrasses over warm season and late emerging crabgrass resulting in an indirect reduction of crabgrass incidence via competition. Fertilization through the application of composted waste (2.5 cm of 50:50 green waste:biosolids, approximating 4 kg actual N per 305 $m^2$) has also resulted in a notable crabgrass population reduction in Bermuda grass [*Cynodon dactylon* (L.) Pers.] (Le Strange and Geisel 2000). In that study, the greatest effect on crabgrass was achieved when the composted waste was applied quarterly at a rate of 6.35 mm surface coverage. Johnson (1981) reported, however, that N applications did nothing to reduce large crabgrass infestations in Kentucky bluegrass. Because crabgrass grows rapidly and has a rather large root system it has relatively high demands for phosphorus (P) and potassium (K) and limiting access to P and K may limit crabgrass growth and competitiveness (Peters and Dunn 1971). For example, Hoveland et al. (1976) found that growth of large crabgrass was significantly reduced (by as much as 40%) when K application rates were reduced from 213 to 40 kg $ha^{-1}$. Similarly, when P application rate was reduced from 90 to 22 kg $ha^{-1}$, growth of large crabgrass was reduced by approximately 45% (Hoveland et al. 1976). The mechanism by which fertilization has resulted in reduced crabgrass incidence has not been made explicit. The ability of $KNO_3$ to reduce the dormancy period and increase germination of large and small crabgrass (Toole and Toole 1941; Delouche 1956; Gallart et al. 2008) suggests that fertilizer applications, especially ones that are timed when crabgrass emergence is starting, may favour crabgrass success in turfgrass. If crabgrass is capable of recruiting even under typical fertilizer regimes, establishment and infestation may still occur if turfgrass becomes stressed.

Crabgrass is competitive under drought conditions, and its germination and growth are also favoured in turfgrass that is over-watered (Cudney and Elmore 2000). In addition, turfgrass that has frequent, light irrigation (e.g., daily), rather than infrequent, heavy irrigation (e.g., once per week) is more likely to be infested with crabgrass (Cudney and Elmore 2000). It has been suggested that subterranean irrigation as opposed to broadcast irrigation may reduce weed seed germination by reducing seed contact with available moisture near the soil surface (Busey 2003). This may be especially true if the majority of weed seeds reside near the soil surface, which has been shown to be the case for small crabgrass in Kentucky bluegrass and tall fescue swards (Gibeault et al. 1985).

Management practices that bury weed seeds in soil can greatly influence weed emergence (Benvenuti et al. 2001; Van Acker et al. 2004) and seed longevity (Masin et al. 2006). Crabgrass recruits preferentially from relatively shallow depths and we know that in field crops reduced or zero-tillage results in significantly greater crabgrass infestations (Mohler and Calloway 1992; Zanin et al. 1997; Cardina et al. 1998; Swanton et al. 1999; Myers et al. 2005). In turfgrass, inversion of the soil horizon as a management strategy, such as a tillage operation, does not occur due to the perennial nature of the crop. Instead, cultivation techniques such as slicing, grooving, spiking and core aeration are used to relieve turf compaction (Harivandi 2002). The impact of tillage on seedling emergence is dependent on the seed's initial distribution throughout the soil profile, its subsequent displacement and the associated change in microsite conditions (Mohler and Galeford 1997).

Coring typically reduces the longevity of crabgrass seed by exposing it to light and encouraging germination (Feldman et al. 1997; Cardina et al. 1998). Consequently, if there is a crabgrass seedbank present, this technique is not recommended in late spring or early summer when crabgrass can germinate, particularly into weakened turfgrass stands (Harivandi 2002). Neal (1994) observed an increase in crabgrass emergence after core cultivating Kentucky bluegrass in early summer, a time when turf species vigour is low and crabgrass germination levels are high. Generally, the impact of turf cultivation on crabgrass success has been studied to a very limited extent.

For all turf and weed management practices timing of application or action relative to the species' recruitment cycle plays an important role in mitigating infestation. This may be especially true for crabgrass management where effective herbicides are not an option. This highlights the importance to crabgrass management of understanding the recruitment nature of crabgrass populations under a variety of practically relevant scenarios. Being able to gauge when and the extent to which crabgrass will emerge in turfgrass scenarios is vital for devising effective management strategies.

## Alternative Herbicides

In jurisdictions where synthetic herbicides are banned from use, alternative herbicides such as bioherbicides, natural or plant based products, or chemicals considered low-risk have become more popular. Some products have been documented to affect crabgrass incidence, although studies have focussed primarily on their effects on large crabgrass specifically (Table 6). Corn gluten meal (CGM) is a by-product of the corn wet-milling process, while corn gluten hydrolysate (CGH) is derived from CGM by the addition of amylase and protease enzymes (McDade and Christians 2001). These products act on germinating seeds and while seedlings emerge normally their root development is inhibited and they die as a consequence of water shortage (McDade and Christians 2001). However, this is only effective if the supply of water is insufficient. By comparison, under greenhouse conditions CGH has demonstrated greater efficacy as a herbicide on crabgrass than CGM (Liu et al. 1994). In field studies, both of these corn-based bioherbicides have been found to be effective on both large and small crabgrass (Christians 1993; McDade and Christians, 2001; Table 6). Both CGM and CGH are also sources of nitrogen (Christians 1993; Christians et al. 1994). The effect of these products as fertilizer has been shown to improve the overall aesthetic quality of turfgrass in field trials when compared with untreated controls (Christians 1993; McDade and Christians 2001). A desirable aspect of CGH (compared with CGM) is its ease of application because it is water soluble (Christians et al. 1994). However, this quality may also result in rapid microbial degradation or leaching and may explain some inconsistency in efficacy (McDade and Christians 2001). Molecules found in crucifers, namely aliphatic (ethyl-, propyl-, butyl-, allyl-, and 3-methylthiopropyl-) and aromatic (phenyl-, benzyl-, and 2-phenylethyl-) isothiocyanates, have also been shown to suppress large crabgrass (Norsworthy and Meehan 2005; Table 6). However, low rates of application may result in increased crabgrass emergence. Previous work showing that low concentrations of isothiocyanates delay germination of some weeds, possibly by inducing secondary seed dormancy, while higher concentrations prevent it (Petersen et al. 2001), supports this finding. Aliphatic and aromatic isothiocyanates can be released into the soil by various mustard species. Consequently, some biopesticide products contain yellow mustard (*Sinapsis alba* L.) and oriental mustard (*Brassica juncea* L. Czern.) seed meal (Earlywine et al. 2007; Earlywine 2009; Table 6). Fungal pathogens have also been trialed as potential bioherbicides for crabgrass control [see, for example, Kenfield et al. (1988), Chandramohan and Charudattan (2002), Li et al. (2002), Evidente et al. (2006, Table 6)]. In many cases the efficacy of potential bioherbicides remains substantively lower than what had been commonly achieved with synthetic herbicides. For example, dazomet (3,5-dimethyl-1,3,5-thiadiazinane-2-thione) applied at 392 kg $ha^{-1}$ can achieve very high levels of large crabgrass control (consistent efficacy ratings over 95%), while oriental mustard seed meal applied at 3360 kg $ha^{-1}$ achieves efficacy levels only in the range of 50% (Earlywine 2009).

## Conclusion

Much of the characterisation of the biology and ecology of crabgrass varies substantially among site-years and whether they were reported in turf or agricultural scenarios. While variation of recruitment biology characteristics and timing is likely due in part to differences in environmental conditions, it may also be genetic. There has been a greater focus on the study of large crabgrass recruitment biology and ecology as compared with small crabgrass. The majority of recruitment studies to date are not in turfgrass systems, possibly because until recently herbicides were used as a blanket solution and, thus, the causative issues were ignored.

Ultimately, effective management of crabgrass in turf should work to create a habitat that discourages crabgrass recruitment and growth. This review shows that this may be accomplished by avoiding low mowing heights, frequent and light watering regimes, aeration during optimal crabgrass germination or into thin turf, and fertilization which favours crabgrass development. The establishment of thick turfgrass swards early in the season and the maintenance of their health throughout the season may be the best overall means to limiting the penetration of crabgrass later in the season, although this has not been thoroughly researched. This is especially important where the use of effective herbicides is not an option.

Table 6. The efficacy of alternative herbicides on large crabgrass in turfgrass

| Herbicide[z] | Application details | Weed control (%) | Citation |
|---|---|---|---|
| *Natural herbicides* | | | |
| Allyl isothiocyanate | 10 000 nmol $g^{-1}$ soil | 98 | Earlywine (2009) |
| Benzyl isothiocyanate | 10 000 nmol $g^{-1}$ soil | 86 | Earlywine (2009) |
| Butyl isothiocyanate | 10 000 nmol $g^{-1}$ soil | 72-79 | Earlywine (2009) |
| Corn gluten hydrolysate[z] | 200 g $m^{-2}$, 1st year | 69 | McDade and Christians (2001) |
| Corn gluten hydrolysate[z] | 200 g $m^{-2}$, 2nd year | 93 | McDade and Christians (2001) |
| Corn gluten meal | 200 g $m^{-2}$ | 86 | Christians (1993) |
| Ethyl isothiocyanate | 10 000 nmol $g^{-1}$ soil | 72-79 | Earlywine (2009) |
| 3-Methylthiopropyl isothiocyanate | 10 000 nmol $g^{-1}$ soil | 100 | Earlywine (2009) |
| Oriental mustard seed meal | 3 360 kg $ha^{-1}$ | 54 | Earlywine (2009) |
| Phenyl isothiocyante | 10 000 nmol $g^{-1}$ soil | 96 | Earlywine (2009) |
| 2-Phenethyl isothiocyanate | 10 000 nmol $g^{-1}$ soil | 95 | Earlywine (2009) |
| Propyl isothiocyanate | 10 000 nmol $g^{-1}$ soil | 72-79 | Earlywine (2009) |
| Yellow mustard seed meal | 2 700 kg $ha^{-1}$ | 72 | Earlywine et al. (2007) |
| Bioherbicides | | | |
| *Curvularia eragrostidis* QZ-2000[yx] | $1.0x10^{6}$ spores $mL^{-1}$ | 99 | Zhu and Qiang (2004) |
| *Curvularia eragrostidis* QZ-2000[yx] | $5x10^{6}$ spores $mL^{-1}$, 150 mL $m^{-2}$ | 61 | Zhu and Qiang (2004) |
| *Curvularia intermedia*[y] | 500 000 spores $mL^{-1}$ | 75 | Walker and Tilley (1999) |
| *Dreschslera gigantea*[y] | $5x10^{5}$ spores $m^{-1}$, 100 mL $m^{-2}$ | 78 | Chandramohan et al. (2002) |
| *Dreschslera gigantea*[y] | $10^{5}$ spores $mL^{-1}$ | 90 | Chandramohan and Charudattan (2001) |
| *Dreschslera gigantea*[y] | 2x3 $10^{7}$ mycelia fragments $mL^{-1}$ | 95 | Shabana et al. (2010) |
| *Exserohilum longirostratum*[y] | $5x10^{5}$ spores $m^{-1}$, 100 mL $m^{-2}$ | 91 | Chandramohan et al. (2002) |
| *Exserohilum longirostratum*[y] | $10^{5}$ spores $mL^{-1}$ | 83 | Chandramohan and Charudattan (2001) |

| Herbicide[z] | Application details | Weed control (%) | Citation |
|---|---|---|---|
| *Exserohilum rostratum*[y] | 5x$10^5$ spores $m^{-1}$, 100 mL $m^{-2}$ | 79 | Chandramohan et al. (2002) |
| *Exserohilum rostratum*[y] | $10^5$ spores $mL^{-1}$ | 83 | Chandramohan and Charudattan (2001) |

[z] Tested on crabgrass alone unless denoted, then tested on a turf/crabgrass combination (Nassau Kentucky bluegrass).
[y] Fungal pathogen; concentrations applied in amended water solutions; applications not described by area are applied in greenhouse until run-off.
[x] Control described by foliar disease incidence unless denoted by ([x]), then biomass dry weight.

Although a wide spectrum of the biology and ecology of large and small crabgrass has been studied, there remain substantive gaps in knowledge. Of the relevant research on crabgrass within turfgrass systems much pertains to control via synthetic herbicides or to trials for emerging bioherbicides. Studies on cultural management techniques are very limited and when these types of studies are conducted they tend to focus on the condition of turfgrass and the indirect effects of competition on crabgrass rather than the direct effects of treatments on crabgrass itself. There is a critical link missing between knowledge of crabgrass recruitment biology and ecology and what this means for management in turf. In particular, there has been a general absence of systematic investigation of non-herbicidal management techniques on the recruitment and establishment of crabgrass where the techniques are chosen based on a consideration of recruitment biology and ecology. With recently implemented bans on cosmetic herbicide use this need is now more urgent and there is a need for research pertaining directly to crabgrass recruitment systems within turf. This shift is necessary because currently available bioherbicide products do not offer the same level of efficacy as conventionally used herbicides. The priority need is for research to determine regional emergence timings of crabgrass within turfgrass ecosystems as well as recruitment response to cultural management techniques that have been devised on the basis of an understanding of the recruitment biology and ecology. This type of research would have the potential to reveal ideal application timings for existing and developing bioherbicides and guide recommendations for the best cultural management practices to deter crabgrass establishment in turf.

## Acknowledgements

This review was made possible with support from the Natural Sciences and Engineering Research Council of Canada and The Ontario Agricultural College at the University of Guelph.

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