Growth responses, competitiveness and control of *Digitaria nuda* (Schumach.) in maize (*Zea mays*)

by

Elbé Hugo

Submitted in partial fulfilment of the requirements for the degree

PhD in Agronomy

In the Faculty of Natural and Agricultural Sciences

Department of Plant Production and Soil Science

University of Pretoria

Pretoria

Supervisors: **Prof CF Reinhardt**

                Dr BJ Vorster

Co-Supervisor: **Dr AEJ Saayman-Du Toit**

January 2014

CONTENTS

iii

iv

v

DECLARATION

I, **Elbé Hugo**, declare that the thesis, which I hereby submit for the degree **PhD (Agronomy)** at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

SIGNATURE: ……………… ……………………….

DATE: ………12 May 2014……………………….

vi

ACKNOWLEDGEMENTS

LIST OF FIGURES AND TABLES

viii

ABSTRACT

Digitaria species infestation levels have recently increased in South Africa due to the prevailing misconception amongst producers and herbicide agents that acetanilide herbicides will control all *Digitaria* spp. equally effective, irrespective of species differences. Since 2008 a relatively unknown *Digitaria* spp was noticed in maize fields and was positively identified as *D. nuda* (naked crabgrass). Research on naked crabgrass world-wide is limited; it has been reported to be of importance in sugarcane in Brazil and is considered as a serious grass weed in West Africa. Growth chamber trials were conducted to elucidate the germination characteristics of naked crabgrass. Germination of fresh naked crabgrass seed was less than 20%. Pre-treatment of fresh seed, by means of soaking seed for 24 h in distilled water, increased germination to 99%. Stored seed (1-yr old) germinated best (100%) in a 0.2 M KNO_3 solution. Naked crabgrass germinated best at constant temperature greater than 25 °C and at fluctuating regimens of 30/15 °C, with alternating light/dark conditions. Naked crabgrass emerged faster and total seedling emergence was 20% higher on clay soil. Above-ground biomass was 5.0 g per plant on clay soil compared to 2.3 g on sandy soil. Seedling emergence was reduced by 27% after burial at a depth of 1 cm and only 5% seeds emerged at a depth of 6 cm. In a replacement series glasshouse trial naked crabgrass was more aggressive with regard to root mass (AI=0.3) and large crabgrass (*D. sanguinalis*) with regard to shoot mass (AI=0.04). Naked crabgrass was more competitive in a wet soil profile (CR=1.88) and large crabgrass in a dry soil profile (CR=2.02). Both grass weeds are making similar demands on the available resources (RYT=1). The competition effect of both naked and large crabgrass was determined in glasshouse trials in two soil types at different watering regimens. A negative linear relationship was recorded between grass density and maize plant height, shoot- and kernel weight. Estimated yield loss of maize varied between 29 and 76% and was described by the hyperbolic equation of Cousens (1985). Large crabgrass had a higher damage coefficient (4.1 on sandy soil) compared to naked crabgrass (3.1 on clay soil). A critical period of weed control was established in field trials for naked

crabgrass. The beginning of the critical period of weed control when a 10% yield loss is estimated varied between the two and six leaf stage of maize, ending at the twelve leaf stage or two weeks after tasseling, indicating a need for season-long control of naked crabgrass. Yield loss of maize in the field trials ranged between 28 and 82% in the season-long weedy control treatments. In field and glasshouse trials the efficacy of naked crabgrass control was evaluated with different herbicides registered on maize. Naked crabgrass is more tolerant to acetochlor and s-metolachlor and started to emerge two weeks after applications. Large crabgrass is still effectively controlled by these herbicides. More than 85% of naked crabgrass was controlled when PRE applications of acetanilide herbicides were followed by triketone herbicides. Indiscriminate identification of all crabgrass species as "large crabgrass" can cause a shift from large crabgrass to naked crabgrass since the latter is more difficult to control. Extrapolation of characteristics and factors affecting germination and growth between similar species is perilous and should be verified. Results of this study proved that both grass weeds are severe competitors of maize, causing significant yield losses, but species specific characteristics could be distinguished and will improve decision making processes significantly to control naked crabgrass effectively in maize.

CHAPTER 1

LITERATURE REVIEW

1.1.   Origin and distribution of *Digitaria* spp.

Digitaria spp. is monocotyledonous annual and perennial grasses, from the Poaceae family, consisting of about 300 species ((http://www.ars.grin.gov). *Digitaria* was described in 1772 and the genus name was derived from *digitus*, which is Latin for "finger", refering to the plant's fingerlike inflorescence. These grasses originated from Europe and were spread across the world as forage grass for the expanding cattle industry in the late 1860's (Mitich, 1988). The common name "crabgrass" refers to the growth habit of these grasses that resembles a crab. *Digitaria* spp. became troublesome after the establishment of wheat and maize which were more profitable and easier to grow (Mitich, 1988). Crab grasses (*Digitaria* spp.) are believed to be one of the first cultivated grains ("foxtail millet") and were a food source for thousands of years before it was regarded as a major weed worldwide (Mitich, 1988). The most common grasses of this genus world-wide are *Digitaria sanguinalis* (L) Scop. (large crabgrass) and *D. ischaemum* (Schreb.) Muhl. (smooth crabgrass) (Kim et al*.,* 2002). Due to their ability to adjust to tropical and temperate conditions it is reported to be a weed in more than 33 crops in 56 countries (Chippindal, 1955; Halvorson and Guertin, 2003; Mitich, 1988).

Thirty-one of described *Digitaria* species are indigenous to southern Africa. Five of these species are naturalised, viz. *D. didactyla* Willd., *D. natalensis* Stent, *D. rukwae* Clayton, large crabgrass and *D. violascens* Link. (http://www.posa.sanbi.org, http://www.biodiversityexplorer.org). Some of the most prevalent species in South Africa are *D. eriantha* Steud. (Common crabgrass / Smuts fingergrass), *D. ternata* (A. Rich.) Stapf. (Black-seed finger grass) and large crabgrass (Botha, 2010; Bromilow, 2010; Van Oudtshoorn, 2009; http://www.posa.sanbi.org). Common crabgrass and black-seed finger

3

grass are perennials and are used as excellent pasture grasses. Local annual *Digitaria* spp. are proclaimed to be troublesome weeds in field crops including large crabgrass, *D. ciliaris* (Retz.) Koeler (Southern crabgrass), *D. velutina* (Forssk.) Beauv. (velvet crabgrass) and *D. nuda* Schumach. (naked crabgrass). Limited research has, however, been done to determine the weed status of the local annual *Digitaria* spp., other than large crabgrass, and to quantify or distinguish their impact on crop yields, as well as their economic impact in crop production in South Africa (Le Court De Billot, 1988). During the late 1980's exceptionally high rainfall and countrywide flooding occurred in Southern African countries. It is believed (in theory) that seed from, especially naked crabgrass, could have spread to the central parts of South Africa's maize (*Zea mays* L.) producing areas. Naked crabgrass has also been reported to be a troublesome weed in West African countries and Brazil (Chikoye et al., 2000; Dias et al., 2005). Another theory is that naked crabgrass spread through animal feed. Nevertheless, since the late 1990's severe *Digitaria* infestations were reported in particular areas in the Free State and Northwest Provinces of South Africa. Most producers and chemical representatives usually identify "finger grass infestation" as large crabgrass, irrespective of species differences. Kok et al. (1989) did a systematic description of the *Digitaria* section in southern Africa and presented five species of which *D. acuminatissima* (Stapf) and *D. nuda* (Schumach.) were not previously recorded. They reported that naked crabgrass only occurred in the north-eastern regions of KwaZulu-Natal and Mpumalanga since it prefers more tropical environments but suggested that this species can be more wide-spread. Although naked crabgrass is listed as occurring in South Africa in summer crop production fields, limited information about the ecology and biology of this particular *Digitaria* sp. is available to determine the weed's interference and impact on crops.

In the early 1950's, large crabgrass was regarded as a grass that can "provide valuable grazing on fallow land" in South Africa, but was also regarded as a troublesome weed in most annual row crops, especially crops within the grass family. During 1978 a national survey was done by the Botanical Research Institute, including more than 71 fields

4

on 15 farms. From this survey weeds were classified into groups according to their abundance in those fields. Large crabgrass was categorized as one of the nine species of primary importance, along with grasses such as *Eluesine coracana* [(L.) Gaertn.] (Goose grass) and *Setaria pallida-fusca* [(Schumach.) Stapf & C.E. Hubb.] (Red bristle grass). *Panicum schinzii* (Hack.) (Sweet buffalo grass) and *Cynodon dactylon* [(L.) Pers.] (Common couch grass), were classified amongst weeds of secondary importance (Wells et al., 1980). Since then limited research has been done in southern Africa with regard to the importance of crab finger grasses as weeds interfering with crop production. Crabgrass species grow in disturbed areas, particularly in gardens and cultivated fields, and are seldom observed in natural veld. Large crabgrass is widespread in southern Africa and occurs mostly in regions with moderate climates (Botha, 2010; Bromilow, 2010; Van Oudtshoorn, 2009). Kok et al. (1989) did, however, predict that naked crabgrass could become more abundant than large crabgrass and southern crabgrass due to incorrect identification in the past (Figure 1.1 and 1.2).

Figure 1.1. Close up comparison of "clean" stems of naked crabgrass and hairy stems of large crabgrass

Figure 1.2. Comparison between tufts of naked crabgrass and large crabgrass

Various taxonomic identification keys (Barkworth et al., 2003; Halvorson, 2003; Launert and Pope, 1989) demonstrated that the morphological characteristics of naked crabgrass are almost similar to those of large crabgrass and *D. ciliaris*, especially early in the seedling stages of these grasses (Figure 1.3). As all the *Digitaria* spp. has similar growth habits and flowering structures, species are therefore distinguished only by minor differences in the flowering structures and leaf pubescence. Crab grasses have typically spreading stems with wide flat leaf blades that lie on the ground with tips ascending. The inflorescence is a panicle in which the spike-like branches are arranged in digitate form. Spikelets are arranged in two rows on an angled or winged rachis. Each spikelet has two florets of which only one is fertile. The first bracts at the base of the spikelets are either very minute or absent (Van Oudtshoorn, 2009). It is therefore very common to wrongly identify these three *Digitaria* species. The most distinguishable characteristic to identify these *Digitaria* species correctly can only be seen on their seed when grasses are physiologically matured. This makes it extremely difficult to identify *Digitaria* spp. during the vegetative stages. Large crabgrass has a very distinct glume on the lower lemma and also has some prickles on the tip of the lower lemma (grabous).

6

Figure 1.3. Comparison between seedling growth of naked crabgrass and large crabgrass.

Several samples of *Digitaria* species have been taken during the period of this study and sent for identification to the South African National Biodiversity Institute's (SANBI) herbarium where most of the samples were positively identified as naked. Naked crabgrass has in most cases no glume on the lower lemma and if visible, it is only a slight shrivel of a glume. The lower lemma is also very smooth without prickles, from there the common name "naked crabgrass" (Figure 1.4). Southern crabgrass has also a definite glume on the lower lemma, but the lower lemma is also smooth like that of naked crabgrass. Seed size can also be a good first characteristic to distinguish between these three species (L. Fish, SANBI, personal communication) (Table 1.1). Large crabgrass consists of culms decumbent or prostate (10 – 30cm) with 5 - 10 reddish or purplish inflorescences, consisting of 4 – 10 racemes which are very long (4 - 18cm) and thin, radiating (winged) atop its stems. Each branch is lined with pairs of tiny spikelets of which one is stalked and the other one without a stalk (sessile). Spikelets are finely ribbed, hairy with swollen bases, flattened on one side and round on the other and the veins of the lower lemma contain small spines. Seed of

7

large crabgrass (caryopses) are straw-coloured, shiny and up to 2mm long. A further distinguished character of large crabgrass is the knee-like bent lower nodes with hairs on stems near each node. Naked crabgrass and velvet crabgrass are also only distinguished by minor taxonomic differences and are very similar to *D. horisontalis* (Willd.) (Kok et al., 1989). Similar species are therefore very difficult to distinguish from large crabgrass in the field and include at this time southern crabgrass, naked crabgrass and velvet crabgrass (Botha, 2010; Clayton and Renvoize, 1982).
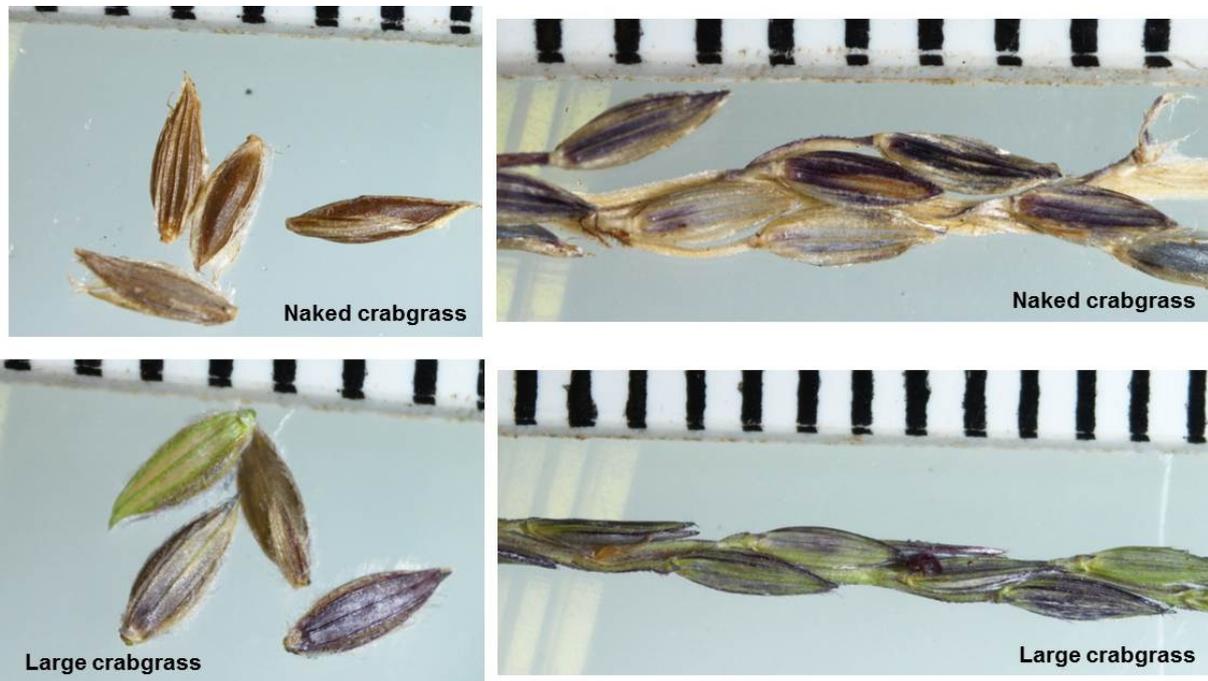
Figure 1.4. Comparison between seed of naked crabgrass and large crabgrass

Table 1.1. Comparison between large crabgrass, naked crabgrass and Southern crabgrass annual grass weed species

Characteristics (taxonomical)	*D. sanguinalis* Large crabgrass	*D. nuda* Naked crabgrass	*D. ciliaris* Southern crabgrass
Habit	Solitary growing	Creeping, sometimes mat-forming	Solitary growing
Culms	20 – 60 cm	10 – 50 cm	20 – 60 cm
Leaf sheaths	Smooth to scaberulous	Scaberulous (hairy)	Scaberulous (bristles)
Ligulae	1-2 mm, truncate, erose	1-2 mm, truncate, erose	Up to 2.5 mm, truncate, erose
Leaf laminae	3-12 x 0.1-0.5 cm, linear, flat, scaberulous on both sides, bulbous bristles on superior surface near base, scaberulous along margin	(2)5-12 x 0.3-0.6 cm, linear, flat, scaberulous on both sides, scaberulous along margin	4-13 x 0.3-0.8 cm, linear, flat, scaberulous on both sides, bulbous bristles on superior surface near base, scaberulous along margin
Inflorescence	(2)4-8 racemes (3)6-12 cm long, erect (2)3-4(5) in inferior whorl (second inferior whorl with 2-3 racemes)	2-10 racemes (3)7-12 cm long in 1 or 2 superposed whorls of 2-5 racemes each	2-9 racemes 6-12 cm long in 1 or 2 superposed whorls (a few solitary along short axis)
Rachis	Triquetrous, broadly winged, 0.7 mm wide, smooth to scaberulous with scabrous margins	Triquetrous, 0.7 mm wide, smooth with scabrous margins	Triquetrous, 1.0 mm wide, smooth to with scabrous margins
Pedicels	2-nate, 0.3-3 mm, triangular, scabrous, scarcely widened at apex	2-nate, 0.5-2 mm, triangular, scaberulous, slightly broadened at apex	2-nate, 0.5-2.5 mm, triangular, scabrous, scarcely broadened at apex
Spikelets	(1.8)2.1-2.8 mm, ovate oblong	2-2.8 mm, oblong to lanceolate	2.7-3.4 mm, oblong glanceolate
Inferior glume	Short, triangular, sometimes truncate/slightly bifid	Shorter than 0.2 mm, poorly developed/absent	0.5 mm, ovate to oblong triangular, often truncate
Superior glume	1/3-2/3 of spikelet, ovate to oblong triangular, 3 nerved, appressed hairy, hairs fine, smooth, acute	1/3-2/3 of spikelet, ovate to oblong triangular, 3 nerved, appressed hairy, hairs fine, smooth, acute, hyaline	2/3-3/4 of spikelet, oblong triangular, 3-nerved, appressed hairy, hairs very fine, smooth, acute
Inferior lemma	As long as spikelet, ovate-oblong, 7-nerved, nerves scabrous, central zone often broad, appressed hairy	As long as spikelet, oblongglanceolate,5- 7-nerved, nerves smooth, mostly equidistant, appressed hairy	As long as spikelet, oblong-lanceolate, 7-nerved, nerves smooth, central zone often broad, appressed hairy, sometimes bristle-hairs, rarely grabous
Superior lemma	As long as to somewhat shorter than spikelet, oblong-lanceolate, slightly acuminate, pale yellow to pale brown, sometimes purplish tinged	As long as to somewhat shorter than spikelet, oblong-lanceolate, acyte, pale yellow to reddish brown, sometimes bluish grey	As long as to somewhat shorter than spikelet, oblong-lanceolate, acute, pale yellow to pale brown, often purplish tinged

*Classification according to *Flora Zambesiaca*, *Digitaria* spp. by Launert and Pope, 1989

9

1.2. Weed status and crop-weed competition

Reports of maize producers experiencing increased grass infestations and low herbicide efficacy in the control of grass weed species have increased since the early 2000's. Although several grass weeds can influence maize production negatively (Botha, 2010; Bromilow, 2010), insufficient control was more evident within the *Digitaria* species complex (crabgrasses), especially in the North West and Free State provinces (see Figure 1.6). This map also indicates the areas where naked crabgass was sampled and field trials were carried out. *Digitaria* species are known to germinate simultaneously with maize (a grass specie as well) and can compete from early in the season for moisture and nutrients (Kim et al., 2002). Late infestation levels of these species are, however, more troublesome and difficult to control and the effect on maize yield have not been determined under South African conditions.

Large crabgrass is known to cause severe infestation problems during the growing season in various crops world-wide (Aguyoh and Masiunas, 2003; Forcella et al., 1992; Fu and Ashley, 2006; King and Oliver, 1994; Monks and Schultheis, 1998). The interference of grass infestations consisting predominantly of large crabgrass and goose grass was found to be more severe and reduced maize yield with 70% when compared to *Cyperus esculentus* (L.) (yellow nutsedge) infestations in maize planted on two soil types in South Africa (Jooste and Van Biljon, 1980). The most prevalent crab grass spp. in the United States of America are regarded as important grass weeds including large crabgrass, smooth crabgrass and Southern crabgrass (Kim et al., 2002).

Effective weed control during the critical periods of crop development prevents serious yield losses and optimizes herbicide applications (Evans et al., 2003a; Norsworthy and Oliveira, 2004; Williams, 2006). The critical period of weed control (CPWC) is defined as the necessary duration of weed control to prevent yield reduction due to weed interference (Hall et al., 1992; Norsworthy and Oliveira, 2004; Page et al., 2009). High weed densities, a

broad weed spectrum and variation in environmental factors between localities have the greatest effect on duration and ending of CPWC in maize (Evans et al., 2003a; Halford et al., 2001; Norsworthy and Oliveira, 2004). Several CPWC have been determined for different weed species in maize (Halford et al., 2001; Hall et al., 1992; Isik et al., 2006, Smitchger et al., 2012). Studies to determine the interference of grass weed species on maize yield were conducted on perennial Johnson grass (*Sorghum halepense* (L. Pers.), volunteer Proso Millet (*Panicum miliaceum* L.) (Anderson, 2000; Ghosheh et al., 1996), *Echinochloa crus-galli* L. Beauv. (barnyardgrass) (Williams 2006), *Eriochloa villosa* (Thumb.) Kunth (woolly cupgrass) (Mickelson and Harvey, 1999; Owen et al., 1993) and giant foxtail (*Setaria faberi* Herrm.) (Hartzler et al., 1999). The CPWC for *Digitaria* spp. interference in maize has not been determined and is believed to be important since the effect of late infestations on yield is uncertain.

The effect of weed competition on various crops has been studied extensively worldwide but is still considered to be a complex field with several factors and interactions between factors playing a role. The severity of weed competition and the manifestation in crop losses will depend on the dominant weed species, density of the infestation and the duration of the infestation period (Rao, 2000). Similar growth habits and nutrient demands between crops and weeds will also increase the severity of competition. The interference of large crabgrass has been reported on maize, snap beans, bell pepper and watermelon, (Agyuyo and Masiunas, 2003; Fu and Ashley, 2006; Hellwig et al., 2002; Monks and Schultheis, 1998). Limited research other than positive identification (Chikoye et al., 2000; Dias et al., 2005; Kok et al., 1989), comparative studies to other *Digitaria* species (Souza et al., 2012) and responses to various herbicides (Dias et al., 2005; Vieira et al., 2010) has been done on naked crabgrass, and none in South Africa. Naked crabgrass is reported to be a serious grass weed in sugarcane in Brazil (Dias et al., 2005). Souza et al. (2012) compared the growth rate and morphological development of naked crabgrass to southern crabgrass and found that southern crabgrass has a higher growth rate and could be more

competitive than naked crabgrass. The competitiveness of *Digitaria* species is to a great extent manifested in their ability to grow in almost any soil type, tolerate stress conditions and to produce abundant seed (Kim et al., 2002; Mitich, 1988).

Allelopathic properties have been recorded for large crabgrass which can inhibit growth of other weed species (Zhou et al., 2013). However, no reports have been found in literature where *Digitaria* species can negatively affect maize growth through allelopathy. While weed interference includes both competition and allelopathy effects on a crop, this study focussed on the competition effect of naked crabgrass on maize.

1.3. Germination characteristics

Understanding weed population dynamics is important to determine and elucidate effective and environmentally friendly weed control strategies. *Digitaria* spp. can occur under a wide range of environmental conditions including tropical to semi-arid regions (Gallart et al., 2010; Holm et al., 1977; King and Oliver, 1994). Large crabgrass, naked crabgrass and Southern crabgrass reproduce only from seed, which are shallow germinators that can germinate until late in a growing season (King and Oliver, 1994). In field germination studies, large crabgrass is one of few weeds that can germinate throughout the growing season with a germination peak two weeks later than most of the other common weeds (Saayman-Du Toit and Le Court De Billot, 1991). Temperature (air and soil), soil water concentration, soil texture and pH influence germination and emergence of *Digitaria* spp. (Chauhan and Johnson, 2008b; King and Oliver, 1994; Steinmaus et al., 2000).

King and Oliver (1994) reported maximum emergence of large crabgrass of 77% at 25 °C and few or no emergence in the field below 15 °C. Large crabgrass showed an average germination of 77.4% between 10 °C and 30 °C, with a base temperature of 16.2 °C (Steinmaus et al., 2000). Southern crabgrass showed optimum germination of 93% at 33 / 25 °C fluctuating temperature regimes. Light can stimulate the germination of southern

12

crabgrass, while large crabgrass germinates regardless of light (Chauhan and Johnson, 2008b). Soil pH and calcium availability influence the growth and competitiveness of *Digitaria* spp. (Buchanan et al., 1975; Pierce et al., 1999). The increase of pH levels reduced the shoot and root dry mass of large crabgrass and its ability to compete can be reduced when raising soil pH levels (Pierce et al., 1999). Some *Digitaria* species are known to have a dormancy period and need pre-chilling or after-ripening before germinating (Biswas et al., 1978). However, research proved that large crabgrass and Southern crabgrass have a low rate of longevity under field conditions, app. 2-3- years (Gallart et al., 2010; Kobayashi and Oyanagi, 2005). No research results could be found on the biology of naked crabgrass with regard to germination, emergence and dormancy. These factors are therefore being addressed in comparative studies in the following chapters.

The burial depth of weed seeds in the soil profile can play a major role in the population dynamics of problem grass weeds (Grundy et al., 2003). Grass weed species are known to accumulate mainly on the soil surface or within the first 0 – 5 cm of soil. Due to the small seed size of most grass weed species, burial depth influences germination and subsequent emergence significantly (Benvenuti et al., 2001; Martinkova et al., 2006; Mickelson and Harvey, 1999; Teuton et al., 2004). Viable seed of large crabgrass declined rapidly after one year and seedling emergence was best from burial depths of 4 to 4.5 cm (Masin et al., 2006). Chauhan and Johnson (2008b) found that southern crabgrass has larger seed than Indian crabgrass [*D. longiflora* (Retz.)], which could not emerge from a burial depth greater than 1 cm, whereas the former emerged from a burial depth of 6 cm, while large crabgrass failed to emerge from this depth (Benvenuti et al., 2001; Chauhan and Johnson, 2008b). Data with regard to longevity and the effect of burial depth on germination and emergence in different soil types are not available yet for naked crabgrass.

1.4. Control of crabgrass

South Africa is one-eighth the size of the USA, consisting of 1.2 million km^{-2} with climatic regions ranging from Mediterranean to subtropical to semi-desert. Only 12% of South Africa's land can be used for crop production of which only 22% is high-potential arable land. The viability of water is the most limiting factor due to unreliable and uneven rainfall throughout the crop production areas. South Africa is self-sufficient in mostly all agricultural products with maize being the most widely grown, followed by wheat, sugarcane and sunflowers. The total area under maize production covers app. 2.8 million hectares with respectively 1.6 million and 1.2 million hectares of white and yellow maize (SAGL, 2013). During the 2012/2013 season 11.7 million tons of maize has been produced with the Free State, Mpumalanga and North-West being the major maize producing areas. The average gross production value for 2012/2013 season was R1 844 $t.ha^{-1}$ (Grain SA, 2013)

Control of annual grass weeds can be problematic due to abundant seed production, persistent seed banks and their ability to germinate and grow in a vast range of environmental conditions (Mortimer, 1991; Chikoye et al., 2000; Kim et al., 2002). The movement of maize producers to reduced tillage practices can also promote a shift in the weed spectrum since most grass weeds are shallow germinators and prevail at high infestation levels where cultivation is absent. Producers therefore tends to rely more on chemical control and hectares planted with herbicide tolerant maize cultivars have increased dramatically since their introduction in 2002 in South Africa. Almost 70% of the total maize production area is planted with Roundup® Ready cultivars (Grain SA, 2012). Consequently, the use of glyphosate applied post-emergence also increased dramatically and 12.6 million litres were sold during the 2010/2011 production season.

Grass weed control in grass crops such as maize has many challenges. Herbicides have to be very specific not to damage the grass crop, but have to control grass weed species effectively (Bernards et al., 2006; Saayman-Du Toit, 2002). Furthermore, applying

14

graminicides (herbicides controlling grass weed spp.) are not a guarantee that all grass weed species will be controlled. Different active ingredients control different grass weed species and sometimes inconsistent control can be experienced within the same grass weed genus (Dias et al., 2005). Some grass weed species can be more tolerant to graminicides than others. Therefore, if a certain grass weed species is not specifically mentioned on a graminicide label, effective control will not be achieved. The most common control practice for grass weeds in maize producing areas in South Africa is to apply pre-emergence herbicides registered on maize at planting, followed by a shallow cultivation depending on crop growth stage and soil moisture status (Bhowmik et al., 1999; Doub et al., 1988). Usually these control measurements would give adequate control of most grass weed species. Post-emergence herbicide applications to control grass weeds are limited and are mostly done with glyphosate where glyphosate resistant cultivars are planted. A large range of herbicides are currently registered for control of grasses on a wide range of crops in South Africa (http://www.CropLife.co.za) (Table 1.2). Most of these herbicides are selective and belong to the chloroacetamide group. The mode of action of this group is to inhibit protein synthesis, disturb cell division and to affect cell membranes (Monaco et al., 2002; Rao, 2000). The primary site of action of these herbicides is the developing leaves beneath the coleoptile and the apical and intercalary meristems near the coleoptile node. Chloroacetamide herbicides control germinating seeds as well as to a lesser extent small emerged seedlings of many grasses, with minimal effect on broad leaf weeds. Grass seeds will germinate but will not emerge due to the absorption of herbicide through the coleoptile. If weed seedlings do emerge they are usually malformed or show abnormal growth. Typical symptoms include whiplashing; where the first leaves do not unfold and the tips are being trapped by the coleoptile causing it to loop (Bernards et al., 2006; Monaco et al., 2002). These symptoms are very pronounced in the crop where herbicide damage occurs due to chloroacetamide application (Figure 1.5).

Figure 1.5. Typical acetochlor damage on maize seedlings (whiplashing)

Several of these herbicides, however, have built in safeners to protect the crop from any herbicide damage (Bernards et al., 2006; Scott-Craig et al., 1998). Safeners added to chloroacetamide herbicides registered in South Africa include dichlormide in acteochlor, furilazole in acetochlor/atrazine/terbuthylazine mixtures and benoxacor in metolachlor. All herbicides registered to control large crabgrass in crops planted in South Africa are listed in Table 1.2

Furthermore, the development of herbicide resistant crops presented a whole new strategy to weed control management systems. Hamill et al. (2000) found that the addition of atrazine and dicamba applied pre-emergence, followed by glufosinate applied post-emergence, enhance the effective control of grass weed species (yellow foxtail [*Setaria glauca* (L.) Beauv.], barnyardgrass and large crabgrass) significantly in gluphosinate-resistant maize. Glyphosate, glufosinate and sulfosate have been reported to control large crab grass more than 90% in several studies (Corbett et al., 2004; Culpepper et al., 1998). Large crabgrass and giant foxtail were also controlled more effectively when acetochlor, metolachlor, atrazine and dimethenamid were applied pre-emergence followed by a mid-post emergence application with glyphosate (Ferrel and Witt, 2002). Early post-emergence application of 2,4-D alone did not control large crabgrass, but when glyphosate was added, control of 95% was obtained (Culpepper et al., 2001). Pre-emergence application of clethodim, setoxydim, fluazifop-P + fenoxaprop-p, fluazifop-P and quizalofop applied alone in

cotton (*Gossypium hirsutum* L.) provided 95% control of large crab grass (Culpepper et al., 1998). However, large crabgrass populations have been reported showing resistance to ACCase inhibitors during 1999 where the accessions were monitored in a carrot (*Daucus carota* L.), onion (*Allium cepa* L.) and maize cropping systems (http://www.weedscience.com (Wiederholdt and Stoltenberg, 1995)). These large crabgrass accessions were resistant to fluazifop-P and setoxydim. Fenoxaprop-ethyl can also provide large crabgrass control of greater than 85%, applied post-emergence on turf grass (Chism and Bingham, 1991). Norsworthy and Meehan (2005) evaluated the herbicidal activity of isothiocyanates on large crabgrass and found that the effectiveness varies among species. Allyl and 3-methylthiopropyl isothiocyanate were more effective on large crabgrass and reduced infestations up to 100%. Hart et al. (2004) found that pre-emergence application of siduron and post-emergence application of quinclorac can effectively control large crabgrass. Very little research has been done on the effective control of naked crabgrass with herbicides. Dias et al. (2005) reported that triazines (ametryn), triazinones (metribuzin) and isoxazolinones (isoxaflutole) showed some control of naked crabgrass and southern crabgrass. Naked crabgrass, however, showed more tolerance to metribuzin. Dias et al. (2005) also reported that producers use chemical control of *Digitaria* spp. without a correct identification of the species and believe that all herbicides can control all *Digitaria* spp. Vieira et al. (2010) also reported that ametryn can effectively control naked crabgrass in sugarcane in Brazil.

To rely only on herbicides to control weeds in crop production can lead to reduced control, resistant weed species populations and a shift in weed species in the seedbank (Davis et al., 2005). It is therefore imperative to apply integrated weed control management programmes for longer lasting effective control (Jones and Medd, 2000; Radosevic et al., 1996). Some grass weed species have the ability to germinate during the whole season and the incorporation of several agronomical practices is needed to ensure effective control. The time of weed control also plays a significant role where optimum weed control is to be

achieved (Hall et al., 1992; Norsworthy and Oliviera, 2004). Nitrogen application, crop rotation, cultivar choice and soil tillage are but a few agronomic tools that can be used in the development of effective weed control management programmes (Chauhan et al., 2006; Evans et al., 2003a; Manley et al., 2002; Mohler and Calloway, 1992; Sosnoskie et al., 2006; Smith, 2006).

18

Table 1.2. Herbicides registered in South Africa for control of large crabgrass (*D. sanguinalis*).

Active ingredient	Site of action	Chemical family	Group (old group name)	Chemical name
cycloxydim	Inhibitors of acetyl CoA caboxylase (ACCase)	Cyclohexanedione	1 (A)	2-[1-(ethoxyimino)butyl]-3-hydroxy-5-(2H-tetrahydrothlopyran-3-yl)-2-cyclohexen-1-one
fluazifop-P-butyl		Aryloxyphenoxy propionate	1	R-2-[4-[[5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoic acid
haloxyfop-R methyl ester			1	(±)-2-[4-[[3-chloro-5-(trifluoromethyl)-2-pyridiny]oxy]phenoxy]propanoic acid
propaquizafop			1	2-(4-aryloxyphenoxy)propionic acid
quizalofop-P-tefuryl			1	R-2[4-[(6-chloro-2-quinoxalinyl)oxy]phenoxy]propanoic acid
chlorimuron-ethyl/metribuzin	Inhibitors of acetolactate synthase (ALS)	Sulphonylurea	2 (B)	2-[[[[(4-chloro-6-methoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]benzoic acid
flumetsulam*		Triazolopyrimidine	2	N-(2,6-difluorophenyl)-5-methyl [1,2,4]triazolo[1,5-a]pyrimidine-2-sulfonamide
benfluralin	Inhibitors of microtubule assembly	Dinitroaniline	3 (K1)	N-butyl-N-ethyl-2,6-dinitro-4-(trifluoromethyl)benzenamine
pendimethalin			3	N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine
trifluralin			3	2,6-dinitro-N,N-dipropyl-4-(trifluoromethyl)benzenamine
chlorthal-dimethyl		None	3	dimethyl-2,3,5,6-tetrachloro-1,4-benzenedicarboxylate
ametryn	Inhibitors of phorosynthesis at photosystem II site A	Triazine	5 (C1)	N-ethyl-N'-(1-methylethyl)-6-(methylthio)-1,3,5-triazine-2,4-diamine
simazine			5	6-chloro-N,N'-diethyl-1,3,5-triazine-2,4-diamine
bromacil		Uracil	5	5-bromo-6-methyl-3-(1-methylpropyl)-2,4(1H,3H)pyrimidinedione
chloridazon		Pyridazinone	5	5-amino-4-chloro-2-phenylpyridazin-3-one
hexazinone		Triazinone	5	3-cyclohexyl-6-(dimethylamino)-1-methyl-1,3,5-triazine-2,4(1H,3H)-dione
metribuzin*			5	4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4H)-one

19

diuron	Inhibitors of phorosynthesis at photosystem II site A (Different binding behaviour from Group 5)	Urea	7 (C2)	N'-(3,4-dichlorophenyl)-N,N-dimethylurea
tebuthiuron			7	N-[5-(1,1-dimethylethyl)-1,3,4-thiadiazol-2-yl]-N,N',-dimethylurea
EPTC*	Inhibitors of lipid synthesis; not ACCase inhibition	Thiocabamate	8 (N)	S-ethyl dipropyl carbamothioate
glyphosate	Inhibitor of 5-enolypyruvyl-shikimate-3-phosphate synthase (EPSP)	None	9 (G)	N-(phosphonomethyl)glycine
glufosinate-ammonium	Inhibitor of glutamine synthetase	None	10 (H)	2-amino-4-(hydroxymethylphosphinyl)butanoic acid
fluorochloridone	Inhibitors of the phytoene desaturase (PDS)	Other	12 (F1)	3-chloro-4-(chloromethyl)-1-[3-(trifluoromethyl)phenyl]-2-pyrrolidinone
oxyfluorfen	Inhibitors of protoporphyrinogen oxidase (Protox)	Diphenylether	14	2-chloro-1-(ethoxy-4-nitrophenoxy)-4-(trifluoromethyl)benzene
sulfentrazone		Triazinone	14	N-[2,4-dichloro-5-[difluoromethyl]-4,5-dihydro-3-methyl-5-oxo-1H-1,2,4-triazol-1-yl]methanesulfonamide
acetochlor*	Inhibitors of synthesis of very long-chain fatty acids	Chloroacetamide	15 (K3)	2-chloro-N-(ethoxymethyl)-N-(2-ethyl-6-methylphenyl)acetamide
alachlor*			15	2-chloro-N-(2,6-diethylphenyl)-N-methoxymethylacetamide
S-dimethenamid*			15	2-chloro-N-[(1-methyl-2-methoxy)ethyl]-N-2,4-dimethyl-thien-3-yl)-acetamide
flufenacet			15	N-(4-fluorophenyl)-N-(1-methylethyl)-2-[[5-(trifluoromethyl)-1,3,4-thiadiazol-2-yl]oxy]acetamide
metazachlor			15	2-chloro-N-(2,6-dimethylphenyl)-N-(1H-pyrazol-1-ylmethyl)acetamide
metolachlor*			15	2-chloro-N-2(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl)acetamide
MSMA	Unknown	Organoarsenical	17 (Z)	monosodium methanearsonate
isoxaflutole	Inhibitors of 4-hydroxyhenyl-puryvate-dioxygenase (4-HPPD)	Isoxazole	27 (F2)	(5-cyclopropyl-4-isoxazolyl)[2-(methylsulfonyl)-4-(trifluoromethyl)phenyl]methanone
mesotrione*		Triketone	27	2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione

*Registered on maize in South Africa

20

1.5. Problem statement and impact of research

Naked crabgrass and large crabgrass are morphologically very closely related to each other. Maize producers often identify crabgrasses as large crabgrass irrespective of the knowledge that subtle differences exists between large crabgrass and the few unknown other *Digitaria* species, such as naked crabgrass. This leads to incorrect identification of grass weeds, subsequently leading to the assumption that all herbicides registered for control of large crabgrass will control these rather unknown *Digitaria* species as effectively. Although the weed status of large crabgrass has been studied worldwide, a lack of knowledge on naked crabgrass is quite evident as shown by the above literature review.

Germination characteristics are species specific and as in the case with most grass species, seed of naked crabgrass showed dormancy and poor germination percentages with initial trials. Different pre-treatments were tested to enhance the germination percentage of naked crabgrass and to shed light on conditions conducive to germination. The aggressiveness and competitive ability of naked crabgrass and large crabgrass was quantified, using a simple replacement series design, tested under two watering regimens. Maize is one of the largest cash crops produced in South Africa and the competition effect of both naked and large crabgrass was determined separately in greenhouse trials to quantify yield losses on two soil types. Since both grass weed and maize crop are C_4 plants, severe competition for the same resources and similar growth patterns can lead to severe maize yield losses. Field trials were conducted over two growing seasons at two localities to determine the critical period of weed control of naked crabgrass to reduce maize yield losses to the minimum (Figure 1.6). Finally, herbicides registered to control large crabgrass effectively in maize were evaluated for control of naked crabgrass. Field trials and glasshouse trials were used to quantify control of both naked crabgrass and large crabgrass on two soil types. Research from this study focussed therefore, primarily on the biology, competition and control of naked crabgrass to clarify challenges producers experienced in some of the major maize producing areas in South Africa to increase sustainable control of this relative unknown *Digitaria* specie

21

that can most probably become more dominant in the coming years. The hypothesis of this study is therefore that the biology between related *Digitaria* species is not similar in all accounts and that the control measures for these grass weeds are species specific.
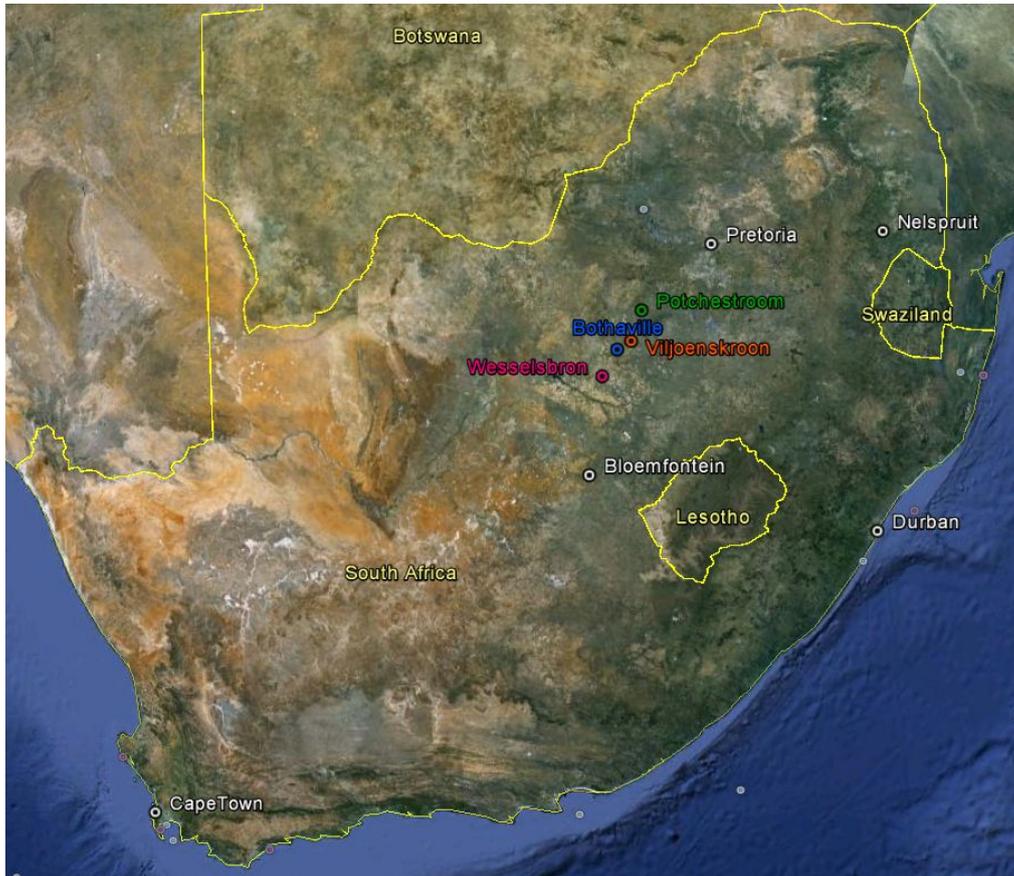
Figure 1.6. National chart of South Africa to show areas where naked crabgrass was sampled and where field trials were conducted.

CHAPTER 2

Germination characteristics of the grass weed *Digitaria nuda* (Schumach.)[1]

E. Hugo[a,b*], A.E.J. Saayman-Du Toit[a], C.F. Reinhardt[b]

aAgricultural Research Council - Grain Crops Institute, Private Bag X1251, Potchefstroom, 2520, South Africa.

bDepartment of Plant Production and Soil Science, University of Pretoria, Pretoria, 0002, South Africa.

[*]Corresponding author *Email address:* HugoE@arc.agric.za (E. Hugo)

Abstract

The effect of various pre-treatments and their interaction with temperature on cumulative percentage and the rate of germination were evaluated for *Digitaria nuda*. Stored and fresh seeds were pre-treated with either 0.02 M KNO_3, soaked in water for 24 h (priming), sterilized with 0.5% NaOCl or heat treated at 60 °C. Seeds were germinated at constant temperatures of 25 and 30 °C and fluctuating temperature regimes of 25/10 and 30/15 °C. The effect of pre-chilling on germination of stored and fresh seed was evaluated at 30/15 °C, and seed emergence in two soil types at different burial depths (0, 0.5, 1, 2, 3, 4, 5 and 6 cm) was also determined. The pre-treatment of stored seed with KNO_3 resulted in the highest germination percentage (100%), whereas the pre-treatment of fresh seed with water for 24 h gave the best germination (99%), at constant temperatures of 25 and 30 °C. Pre-chilling of seed increased germination by more than 30%. Emergence from clay loam soil was greater compared with emergence from sandy loam soil. Total seedling emergence decreased exponentially with increasing burial depths with only 5% of seed germinating from a burial depth of 6 cm. [1]

23

Results from this study showed that germination requirements are species specific and knowledge of factors influencing germination and emergence of grass weed seed can assist in predicting flushes in emergence allowing producers to implement control practices more effectively.

Keywords: burial depth; germination; potassium nitrate; priming; soil type; temperature

2.1. Introduction

Digitaria nuda (Schumach.), commonly known as naked crabgrass, is a relatively unknown *Digitaria* grass species in South African cropping systems. It has recently been positively identified in maize fields in the Free State and North-West Provinces of South Africa. Although *D. nuda* is listed as a weed occurring in crop fields in South Africa, and other countries to the north in Africa, very little information about the ecology and biology of this *Digitaria* grass species is available to establish its weed status and impact on crops (Botha, 2010; Bromilow, 2010; Grabrandt, 1985).

Various taxonomic identification keys (Barkworth et al., 2003; Launert and Pope, 1989; Webster, 1983) have demonstrated the morphological similarities between *D. nuda* and the more common *D. sanguinalis* (L) Scop. (large crabgrass) and *D. ciliaris* (Retz.) Koeler (southern crabgrass). The most distinguishable characteristic with which to identify these *Digitaria* spp. correctly can, however, only be seen on the seed when grasses are physiologically mature, making it extremely difficult to distinguish at the seedling stage. *Digitaria sanguinalis* has a very distinct lower glume on the lower lemma and also has some spicules on the lateral veins of the lower lemma. *Digitaria nuda* has no lower glume on the lower lemma in most cases, and if visible, it is only a slight shrivel of a glume. The lower lemma is also very smooth with no spicules on the lateral veins, hence the common name

24

"naked crabgrass". *Digitaria ciliaris* also has an inferior lower glume on the lower lemma, but the lower lemma is smooth like that of *D. nuda* and the upper lemma is longer. Kok et al. (1984, 1989) made a systematic description of the *Digitaria* section in southern Africa and presented five species; including *D. acuminatissima* (Stapf) and *D. nuda* that were not previously recorded. They found that *D. nuda* only occurred in the north-eastern regions of KwaZulu-Natal and Mpumalanga since it prefers more tropical environments, but it was suggested that this species could be more wide-spread due to incorrect identification.

Research on the weed status of *Digitaria* spp. was mostly done on large crabgrass in South Africa (Wells et al., 1980). In field germination studies *D. sanguinalis* is one of few weeds that can germinate throughout the summer growing season with a germination peak two weeks later than most of the common weeds found in maize fields (Saayman-Du Toit and Le Court De Billot, 1991). Competition of grass infestations, which were dominated by large crabgrass and African goosegrass (*Eleusine coracana* subsp. Africana (K.-O'Byrne) Hilu & De Wet), reduced maize yield up to 70%, and was more severe than *Cyperus esculentus* (L.) (yellow nutsedge) infestations (Jooste and Van Biljon, 1980). *Digitaria sanguinalis* is, however, known to develop high infestations and cause severe competition problems in various crops world-wide (Aguyoh and Masiunas, 2003; Forcella et al., 1992; Fu and Ashley, 2006; Kim et al., 2002; King and Oliver, 1994; Monks and Schultheis, 1998). *Digitaria nuda* has been identified as a troublesome weed in West African countries and Brazil, especially in sugarcane production (Chikoye et al., 2000; Dias et al., 2005). Prior research on *D. nuda* is limited to its taxonomy while its biology and germination ecology are unknown and cannot be inferred from research on other *Digitaria* spp.

Specific requirements for effective germination often differ amongst related weed species and a slight variation in environmental conditions can increase or decrease the rate of their emergence (Hartzler, 1999). Knowledge on the biology and germination characteristics of weeds can be an important tool when implementing integrated weed control strategies, and can be used to prevent significant numbers of new weed seeds being added to the soil seed

25

bank (Chauhan and Johnson, 2009; Hartzler, 1999). Initial germination and the consistency of emergence of a species can support the decision making process for producers for optimal timing of tillage and herbicide applications. Temperature and soil water content are two of the most important factors influencing germination and emergence of weed species (Chauhan et al., 2006; Ghorbani et al., 1999). The germination characteristics of *D. sanguinalis* and *D. cilliaris* have been extensively studied (Chauhan and Johnson, 2008a, 2008b; Gardener, 1996, Halvorson and Guertin, 2003), but no such studies exist for *D. nuda*.

Preliminary germination tests on *D. nuda* showed very poor germination (<20%) and seed dormancy is expected to be the main reason. Most grass species exhibit some form of dormancy where low germination percentages are experienced despite prevailing favourable conditions. Several treatments that promote or enhance germination can be used to break physiological dormancy and have been used to do so in *D. sanguinalis* and *D. ciliaris* (Chauhan and Johnson, 2008a, 2008b; Gallart et al., 2008; Moreno and McCarty, 1994).

The objectives of this study were to determine germination characteristics of *D. nuda* utilising various pre-treatments aimed at breaking dormancy and increasing seed germination using constant and fluctuating temperature regimes in order to identify optimal germination conditions for each of the pre-treatments. Knowing the optimum temperature range in which a specific weed species germinates could shed light on the biology of such a species and can be useful in predicting significant flushes of emergence, leading to more pro-active and practicable control measures. Furthermore, the influence of soil type and seed depth below the soil surface was also investigated to determine effects on seedling emergence.

2.2. Materials and methods

2.2.1. Seed collection

26

Digitaria nuda seed was collected annually from physiologically mature plants during March and April from 2007 to 2011 at the research station of the ARC-Grain Crops Institute, Potchefstroom (North-West Province, 26°43'41.9" S, 27°04'47.8" E). Since *D. nuda* is a relatively unknown grass species in South Africa, at least with regard to its distribution, racemes sampled in each year were sent to the National Herbarium of the South African National Biodiversity Institute to be positively identified. After collection, seed was left to dry in a greenhouse at 30/15 °C (day/night) temperature range for two weeks. Seed was removed from racemes by hand and cleaned from inert material to obtain experimental samples. Samples of each year were kept separate and stored in air-tight plastic containers at 15 °C. Seed properties are summarized in Table 2.1.

Table 2.1. Seed properties of *D. nuda* collected in Potchefstroom from 2007 to 2011.

Seed year collected	Seed mass (g.100^{-1})	Pure seeds[a]	Caryopsis present[b]	Viable seed[c]
			%	
2007	0.189	94	43	28
2008	0.199	98	59	50
2009	0.188	91	31	14
2010	0.248	96	57	58
2011	0.292	94	78	49

[a] seeds of *D. nuda* per sample; [b] intact, germinable seeds; [c] viable seeds determined with tetrazolium tests.

2.2.2. Germination tests

Germination tests were done using both 1-year old seed (harvested in 2010) and fresh seed (harvested in 2011) of *D. nuda* to compare germination. Seed harvested during 2010 was

27

stored in air-tight plastic containers at 15 °C following drying until commencement of germination tests in 2011. Five different seed pre-treatments to enhance germination of *D. nuda* were applied to both stored (1-yr old) and fresh seed: 1) KNO$_3$ applied at 0.02 M in place of distilled water, 2) immersing (priming) seed for 24 h in distilled water (water 24 h), 3) sterilization in 0.5% NaOCl solution for 10 minutes followed by rinsing with distilled water, 4) heat treatment of seed in brown paper bags at 60 °C for 24 h (heat treatment), and 5) control treatment where seed was not pre-treated.

One hundred seeds of *D. nuda* were placed separately in polyethylene containers (22 x 15 x 5.5 cm) on brown Anchor germination paper (once folded) for each treatment, which was replicated four times (total of 400 seeds per treatment). Distilled water (13 ml) was added to the germination paper to provide moisture, except where KNO$_3$ was used. Since temperature can play a major role in the germination of grass seed, all germination treatments were repeated at constant temperatures of 25 and 30 °C, and fluctuating temperature regimes of 25/10 and 30/15 °C using growth chambers with day/night (14 h light/10 h dark) conditions. These temperatures and day/night light regimens were chosen to reflect temperature and diurnal variation in maize- producing areas in South Africa where *D. nuda* and *D. sanguinalis* commonly occur as troublesome weeds in maize fields (Table 2.2). Germinated seeds were counted and removed when a white protrusion of the radicle was observed. The duration of each trial was 30 days.

28

Table 2.2. Average 10-year maximum and minimum temperatures for four South African localities where severe *D. nuda* infestations had been reported.

Locality	Potchefstroom		Viljoenskroon		Bothaville		Wesselsbron	
GPS co-ordinates	27°04'31.91'' S 26°43'50.18" E		26°54'32.29" S 27°10'45.05" E		26°40'55.88" S 27°18'12.31" E		26°26'30.69" S 27°41'27.85" E	
	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin
	°C							
Early[a]	28.80	13.46	29.86	11.56	30.28	9.62	29.79	11.92
Mid	29.05	16.51	30.72	15.6	30.15	15.2	31.03	15.76
Late	29.08	15.02	29.01	13.86	28.29	13.8	28.94	14.19

[a]Crop growth season was divided into early season (Oct to Nov), mid-season (Dec to Jan) and late season (Feb-March).

2.2.3. Effect of pre-chilling

Minimum temperatures during winter months in areas where *D. nuda* occur fluctuate between 0 and 10 °C, with frost occurring regularly. *Digitaria nuda* seed from stored (1-yr old) and fresh samples was pre-chilled for three months at 4 °C after which germination tests were carried out as described above. Germination tests were, however, only done at the fluctuating temperature regime of 30/15 °C (14 h light/10 h dark) in a growth chamber, thus simulating seasonal temperature fluctuations.

2.2.4. Data analysis of germination trials

A split-plot factorial analysis was done on data with temperatures (4 factors) as whole plots, and treatments and seed age (5 X 2 factors) as sub-plots. The means of significant interaction effects were compared using Fisher's Protected t-LSD at a 5% significant level using GenStat for Windows 15th edition (Payne 2011). Mean germination time (MGT) was determined for all treatments, temperature regimes and seed age. Cumulative germination was normalized in

29

each treatment, setting the maximum germination at 100% (King and Oliver, 1994). A germination index was determined to compare germination rates between treatments and temperatures using the equation described by Maguire (1962):

$$GI = \Sigma n_i / t_i \qquad [2.1]$$

where n_i is the percentage seeds germinated at the ith day and t_i is the number of days recorded from the onset of the experiment to the last day on which seeds germinated. The Mitscherlich curve was fitted on cumulative germination to determine time to 50% of final germination (Brown and Mayer, 1988; Ismail et al., 2002):

$$Y = M[1-\exp(-K(t-L)] \qquad [2.2]$$

where Y = cumulative germination at time t, M = asymptote (theoretical maximum for Y), L = the time (day) seed started to germinate, K = rate of increase in germination.

2.2.5. Effect of burial depth

The effect of different burial depths on the emergence of *D. nuda* seedlings was studied in two soil types in a greenhouse at a temperature regime of 30/15 °C (day/night), which simulated the expected average regime in the respective maize production areas (Table 2.2). Tetrazolium tests (ISTA, 2010) were done on stored, non-germinated seeds collected in 2007, 2008, 2009 and 2010 to determine the percentage viable (fresh) and non-viable (dead) seed for each seed year. Soil was collected from each of two experimental farms of the Agricultural Research Council namely ARC-Grain Crops Institute in Potchefstroom and ARC-Small Grains Institute in Bethlehem (28°09'55.12" S, 28°18'32.97" E). Potchefstroom and Bethlehem soils had a clay content of 36% (Hutton clay loam) and 16% (Avalon sandy loam), respectively. Soils were sterilized separately with methyl bromide, sieved and placed in square polyethylene containers (275 x 275 x 145 mm). Each container was marked in cm to enable

30

planting at specific depths below the soil surface. Soil temperature for each increment was measured; there was less than 1 °C difference between the soil surface and 6 cm depth.

One hundred seeds of each seed year were placed on the soil surface at the respective burial depths of 0, 0.5, 1, 2, 3, 4, 5 and 6 cm and covered with soil. Soil was rolled firmly after seeding at each burial depth to ensure good soil-seed contact. The experiment was a randomized complete block design and each treatment was replicated six times (treatments were replicated three times; whole experiment was repeated for each soil type). Moisture content at field capacity (FC) of the soils was determined gravimetrically by means of weighing of containers prior to and after water was applied in excess and thereafter allowing water to drain freely for 12 hours. The clay loam (Potchefstroom) and sandy loam (Bethlehem) soil was watered daily with 200 and 150 ml, respectively, to maintain soil as close as possible to FC in order to prevent water stress from influencing seedling germination. Chemicult, a commercial liquid fertilizer, diluted with water as specified on the label, was applied to all treatments 14 days after seeding at a fixed volume of 100 ml per container. Holes in the bottom of the containers ensured free drainage of water. Seedlings were counted after emergence of the coleoptile and development of the first fully unfolded leaf (ligula clearly visible). Mean time to emergence (MTE) was adapted from the mean germination time formula and calculated as follows:

$$MTE = \Sigma(n \times g)/N \qquad [2.3]$$

where n is the number of emerged seedlings on day g and N is the total number of seedlings emerged.

Total number of plants that emerged from each burial depth was counted daily for 22 days after planting (DAP) when emergence was no longer observed in both soil types. The maximum total of *D. nuda* seedlings that could potentially emerge from each seed year was determined by the sum of the percentage normally germinated seedlings and the percentage viable seed determined from the tetrazolium tests. The trial was terminated 42 DAP when

31

plants were cut at the soil surface. Mean dry mass of leaves and stems was determined for each treatment after drying overnight at 60 °C. Total emergence of seed sampled in 2009 was less than 12%, and viable seed was only 14%, hence, it was decided to omit 2009 data from analyses. Data for seed from 2007, 2008 and 2010 were subjected to ANOVA using GenStat for Windows 15th edition (Payne, 2011). Regression analysis was used to determine the relationships between burial depth, seed year and soil type using an exponential model to describe the relationship:

$$E = A_{max}e^{(-bx)} \quad [2.4]$$

where E = emergence (%) at seed burial depth b, A_{max} = maximum potential plants emerged, and x = slope.

2.3. Results

2.3.1. Germination tests

Germination patterns of *D. nuda* differed greatly between seed ages, pre-treatments and temperature regimes. Cumulative germination to determine 50% of final germination is shown in Figure 2.1 only for control, KNO_3 and water 24 h pre-treatments at constant 25 and 30 °C and fluctuating 25/10 and 30/15 °C temperature regimes (model parameters Table 2.3). The heat pre-treatment failed to reach 50% of final germination at constant and fluctuating temperature regimes. Only stored seed that was sterilized showed germination greater than 50% and these pre-treatments will be discussed under final germination. At 25 °C, stored seed treated with KNO_3 and fresh seed soaked in water for 24 h reached 50% of final germination within three days. One year old seed soaked in water and fresh seed in control treatments reached 50% of final germination only after 16 and 18 days, respectively, but failed to reach germination percentages greater than 60%. The same tendency was observed for stored and fresh seed in the KNO_3 and 24 h water treatment at 30 °C, but the control treatments failed to reach 50% of final germination. One year old seed soaked in water for 24 h reached 50% of

32

final germination within 5 days at 30 °C. Seed in control treatments failed to reach 50% of final germination at 30 °C. Both seed ages of *D. nuda* seed failed to reach 50% of final germination in all treatments at the fluctuating 25/10 °C temperature regime. At the 30/15 °C regime stored seed soaked in water for 24 h took six days to reach 50% of final germination, while fresh seed took 19 days. One year-old seed in control treatments took 14 days and fresh seed treated with KNO_3 took 19 days to reach 50% of final germination.

Seed, regardless of age, that started to germinate early (within three to six days) reached final germination percentages of between 80 and 100%. Seed that germinated more slowly over extended periods showed mostly germination of less than 50%. Low and prolonged germination in control treatments and failure to reach 50% of final germination accentuates the difficulty experienced with seed germination of *D. nuda*.
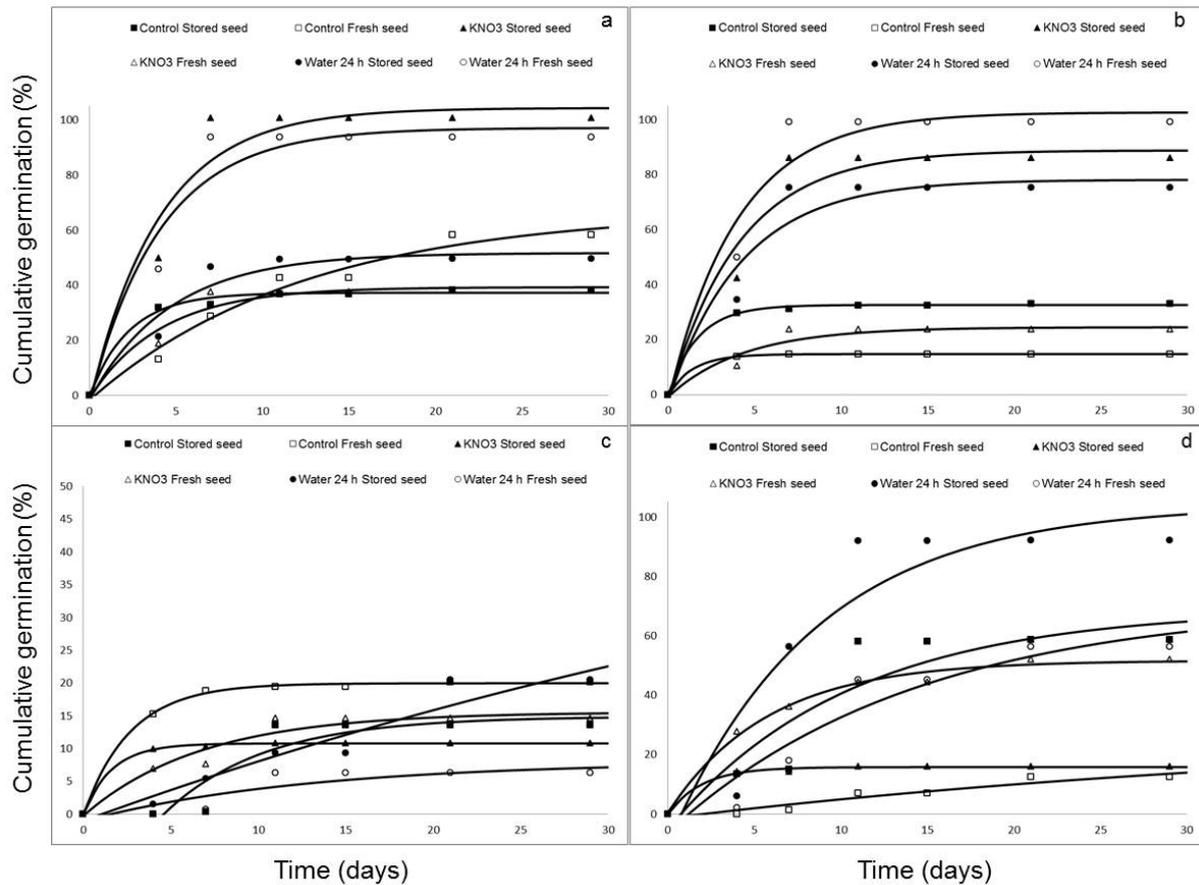
Figure 2.1. Cumulative germination patterns of stored (1-yr old, solid legends) and fresh (open legends) *D. nuda* **seed at constant temperatures regimes of (a) 25 and (b) 30 °C and fluctuating temperatures of (c) 25/10 and (d) 30/15 °C for control, KNO₃ and soaking in water for 24 h treatments. (Symbols are the actual data and lines are the predicted values fitted to the Mitscherlich curve Y = M[1 - exp(- K(t - L))], using the values shown in Table 2.3)**

Table 2.3. Parameter estimates of the logistic function (Mitscherlich curve) fitted to cumulative germination in Figure 1.

Parameter[a]	Temperature regime (°C)					
	25					
	Control	Control	KNO$_3$	KNO$_3$	Water 24 h	Water 24 h
	Stored	Fresh	Stored	Fresh	Stored	Fresh
M	37.239	67.063	104.367	39.26	51.688	97.117
K	0.43232	0.08057	0.24479	0.24012	0.21418	0.24318
L	-0.00614	0.31316	0.09293	0.08986	0.13386	0.09593
	30					
M	32.698	14.83	88.902	24.573	78.225	102.731
K	0.58614	0.69493	0.24393	0.22949	0.23466	0.24779
L	-0.00056	0.00005	0.09453	0.12594	0.11357	0.08765
	10/25					
M	14.88	19.946	10.773	15.557	63.662	7.995
K	0.17343	0.3696	0.61049	0.14732	0.01511	0.07798
L	4.60286	0.00109	-0.00058	0.10328	1.07664	1.59304
	15/30					
M	68.986	28.765	15.782	51.632	104.097	70.871
K	0.09566	0.02369	0.51015	0.17457	0.11887	0.06988
L	0.74363	2.01271	-0.00287	-0.0553	0.78573	1.1946

[a] M = asymptote (theoretical maximum for Y), K = rate of increase in germination, L = the time (day) seed started to germinate.

Although temperature and pre-treatments had the greatest effect on mean germination time (F=143.00, P<0.001; F=28.48, P<0.001, respectively), a significant interaction between temperature, pre-treatments and seed age was recorded (F=8.95, P<0.001). The mean

35

germination time for *D. nuda* was between five and seven days after seeding for most pre-treatments at constant temperatures of 25 and 30 °C, only the control and heat pre-treatment for fresh seed took significantly longer to germinate (13 to 20 days). Germination at fluctuating temperature regimes took twice as long in most pre-treatments with no further germination after 20 days.

Seed age of *D. nuda* had the greatest effect on final germination (F=63.08, P<0.001) followed by temperature (F=46.90, P<0.001) and pre-treatments (F=45.41, P<0.001). All the possible interactions between seed age, temperature and pre-treatments were, however, significant and are shown in Table 2.4 (F=13.24, P<0.001). The lowest germination for stored and fresh seed was recorded in the fluctuating temperature regime of 25/10 °C and varied between two and 20% over all pre-treatments. Germination of fresh seed increased by more than 40% when soaked in water for 24 h at constant temperature of 25 °C. In contrast, the opposite pattern was found at the fluctuating temperature regimes of 30/15 °C: germination of stored seed was greater than that of fresh seed. Potassium nitrate increased germination of stored seed by more than 60% at both constant temperatures of 25 and 30 °C. The priming of fresh seed with water showed, however, the best germination (>94%) at both constant temperatures. Sterilized stored seed showed germination of between 57 and 73% at both constant temperatures of 25 and 30 °C and fluctuating temperatures of 30/15 °C. Heat pre-treatment of seed did not enhance germination for either fresh or stored seed.

Table 2.4. Effect of different temperature regimes and germination treatments on final germination (%) of stored (1-yr old) and fresh _D. nuda_ seed.

Treatment	Temperature regimes (°C)								
	25		30		10/25		15/30		
	Stored	Fresh	Stored	Fresh	Stored	Fresh	Stored	Fresh	Mean[a]
Control	38.25	56.39	33.13	11.11	13.55	20.14	58.74	12.50	30.48b
KNO$_3$	99.57	38.19	85.85	23.61	10.84	14.58	15.97	29.86	39.81c
Heat treatment	34.94	0	31.33	11.81	9.33	22.92	42.47	24.30	22.14a
Sterilized	64.46	12.50	57.23	38.89	2.41	2.78	72.89	19.45	33.83bc
Water 24 h	49.70	93.75	75.30	99.31	20.48	6.25	92.17	56.25	61.65d
Mean[b]	57.38d	40.17c	56.57d	36.94bc	11.32a	13.33a	56.45d	28.47b	
Mean[c]	48.78b		46.76b		12.33a		42.46b		

LSD$_{(Temperature \times Treatment \times Seed\,age)}$ = 18.02

[a] mean germination for treatments, [b] mean germination for seed age and temperature interaction, [c] mean germination for temperature. (Means within columns or rows followed by the same letter(s) do not differ significantly at P=0.05).

A significant interaction between temperature, pre-treatments and seed age was also recorded for germination rate of _D. nuda_. Results obtained for germination rate were similar to that of final germination where the highest germination rate was recorded for fresh seed soaked in water, followed by stored seed that was sterilized and treated with KNO$_3$, at constant temperatures (data not shown). Therefore, the best germination (100%) for stored _D. nuda_ seed can be achieved where seed is germinated in KNO$_3$ at 25 °C, while fresh seed has to be soaked in water for at least 24 h prior to conducting germination tests at 30 °C.

2.3.2. Effect of pre-chilling

A significant interaction between pre-chilling, pre-treatments and seed age was recorded for all parameters tested (MGT: F=31.25, P<0.001; Germination: F=15.31, P<0.001; GI: F=10.58,

P<0.001). Seed that was not pre-chilled germinated within six days only when treated with KNO$_3$. Pre-chilled fresh and stored seed did, however, germinate faster in all the other pre-treatments and took between seven and nine days to germinate compared to 12 and 22 days where seed was not pre-chilled (data not shown). Although the interaction effect on germination will be discussed, it is worth mentioning that the main effect of pre-chilling increased germination by 33%. Germination of stored seed was significantly greater in pre-chilled seed that was either treated with KNO$_3$ or pre-treated at 60 °C. Pre-chilling did not improve germination significantly for stored seed in the control, sterilized and soaking in water pre-treatments. Germination was, however, significantly greater in pre-chilled fresh seeds in all pre-treatments, except where seed was pre-treated with heat (Figure 2.2).
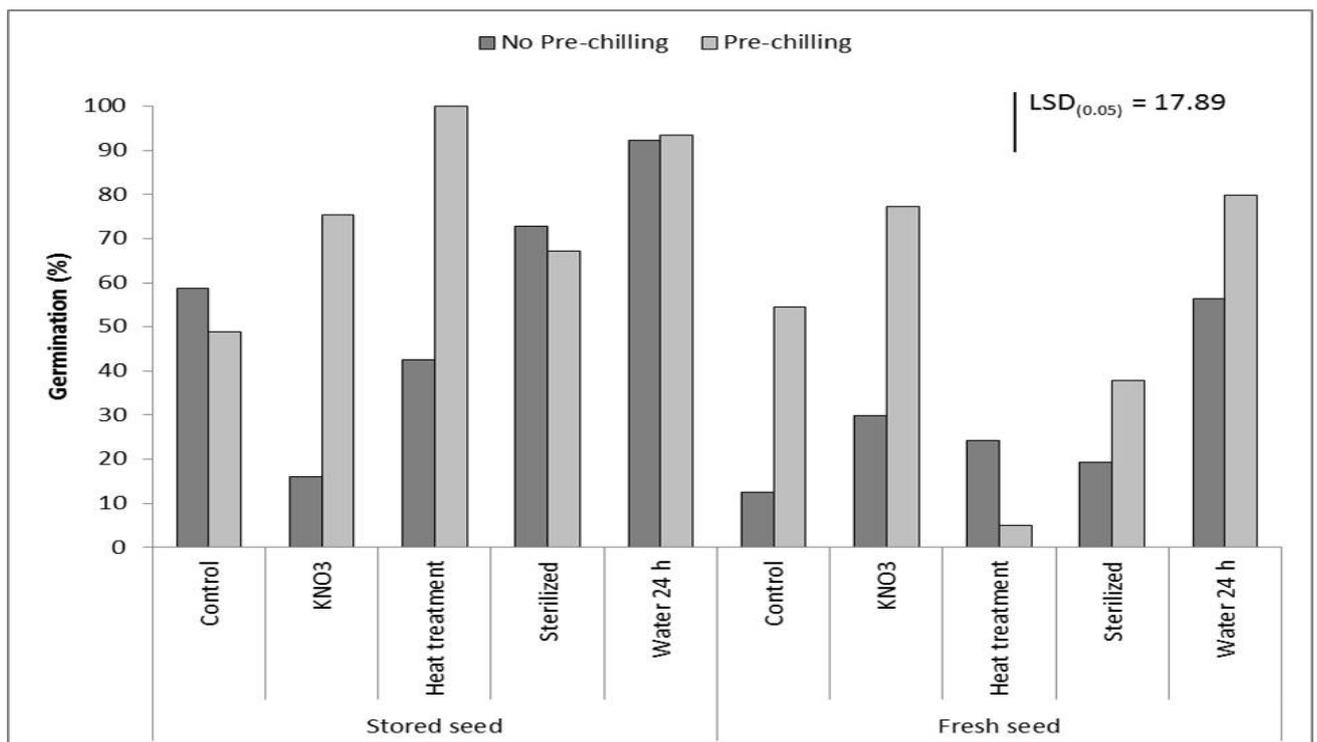
Figure 2.2. Effect of pre-chilling on the germination of fresh and stored (1-yr old) *D. nuda* **seed subjected to various pre-treatments to enhance germination at fluctuating 30/15 °C temperature regime (Significance determined at P=0.05 according to Fisher's LSD$_{(Pre-chilling\ x\ Pre-treatment\ x\ Seed\ age)}$)**

38

2.3.3. Burial depth

Burial depth was the only main effect that influenced MTE significantly (F=5.10, P<0.001) and no significant interactions were recorded for this parameter. Seedlings emerged more rapidly when placed on the soil surface and at depths of 0.5 and 1 cm (9 days). Seed buried deeper than 3 cm resulted in slower emergence of up to 15 days after seeding. Only soil type (F=30.19, P<0.001) and burial depth (F=15.57, P<0.001) significantly affected dry mass of *D. nuda;* no interactions were significant (soil type, burial depth, seed year). Dry mass harvested from clay loam soil was more than double the mass produced on sandy loam soil (5.0 and 2.3 g, respectively data not shown). Dry mass decreased with an increase in burial depth (Figure 2.3). The highest dry mass for grass seedlings was recorded for seedlings emerging from seed at a burial depth of up to 2 cm, but 40% reduction in dry mass was recorded where seed was buried deeper than 4 cm.

39
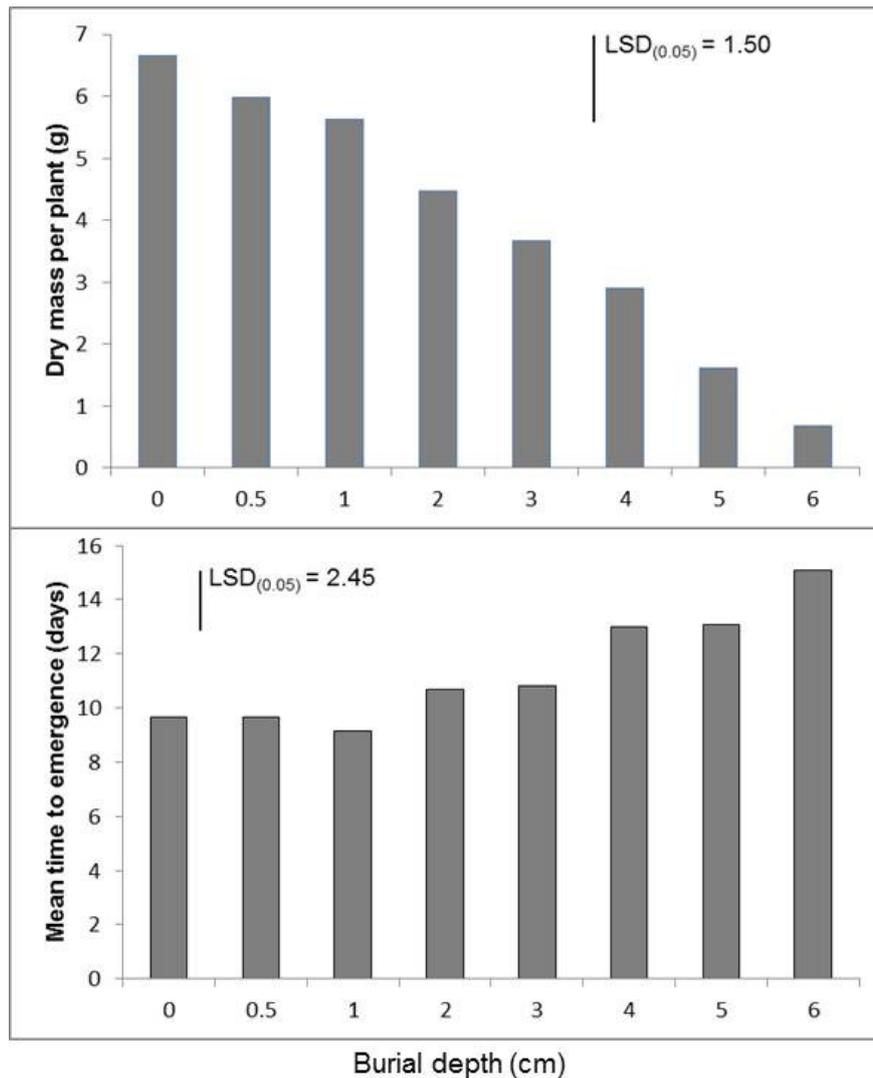
Figure 2.3. Effect of burial depth on mean time to emergence and dry mass per plant of _D. nuda_ seedlings harvested 40 days after seeding (Significance determined at P=0.05 according to Fisher's LSD)

Total plants emerged were significantly influenced by soil type, burial depth and seed year, but no significant interaction effects were recorded (Figure 2.4). _Digitaria nuda_ emergence was 20% greater in clay loam compared with sandy loam soil. The lowest total plant emergence was recorded for the oldest seed sample (2007), but no significant difference was observed between seed harvested from 2008 and 2010. Total plant emergence decreased exponentially with increasing burial depth. Emergence was reduced by 27% after

40

burial at 1 cm and by 61% at a burial depth of 3 cm. Only 5% of *D. nuda* seed emerged from a burial depth of 6 cm.
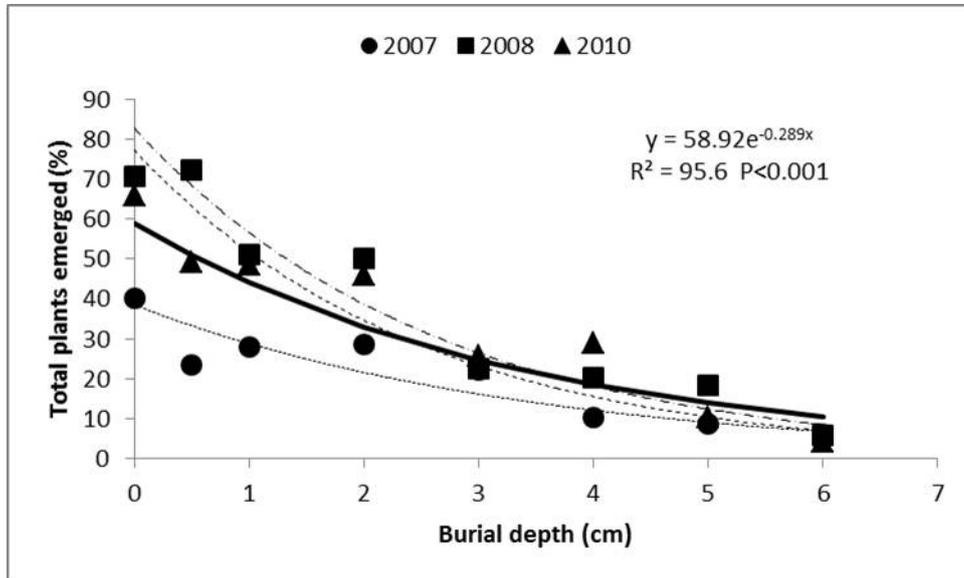
Figure 2.4. Effect of increasing burial depth on the total plants of *D. nuda* emerged (solid line represent mean and dashed lines indicates relationship for each seed year).

2.4. Discussion

Digitaria species reproduce mainly by seed, and most seed shows some dormancy after shedding (Gardner, 1996), but can germinate throughout the season in cycles or flushes when favourable conditions prevail during the summer months coinciding with maize production. There is considerable variation in the timing of seed maturation with *Digitaria* spp. and it is difficult to collect large seed samples with uniform maturity. This and the fact that each plant genotype interacts with the environment during maturation could explain in part, the variation in germination reported for *D. nuda* (Taylorson and Brown, 1977). Although initial germination of stored *D. nuda* started at five days, germination was very low (<30%) and most seed had still not germinated 20 days after seeding without any pre-treatment of seed. Storage alone could not break the dormancy that may be present in freshly harvested *D. nuda* seed effectively. Several studies with *D. sanguinalis* have shown that storage of seed for periods

41

longer than six months can be enough to increase germination significantly (Gardner, 1996; King and Oliver, 1994; Toole and Toole, 1941; Zhang et al., 2012). Gardner (1996) found that fresh *D. sanguinalis* seed took a minimum of 196 days (6.5 months) to germinate while Toole and Toole (1941) reported 7 to 14 days for seed stored for one year.

Germination rate and seedling development are greatly dependent on temperature and according to Steinmaus et al. (2000) is the most important factor regulating germination of non-dormant seed. The daily fluctuating temperature regimes experienced in the field at localities where severe *D. nuda* infestation occur were simulated in growth cabinets to compare with constant temperature treatments. The higher fluctuating temperature regime of 30/15 °C increased mean germination of *D. nuda* seed significantly (>70%), but did not differ significantly from the constant temperatures of 25 and 30 °C. Specific pre-treatments in combination with temperature yielded the highest germination for fresh and stored *D. nuda* seed.

Germination of *D. sanguinalis* was found to be optimal at temperatures between 20 and 30 °C and has a base temperature of 16.2 °C (King and Oliver, 1994; Steinmaus et al., 2000). Fluctuating temperatures have been found to be an important stimulus and even may be a requirement for certain annual grass weed species to germinate successfully (Nishimoto and McCarty, 1997). Due to the small seed size (2.0 to 2.8 mm) and light weight (100 seed weight = 0.22 g), most of the seed of *D. nuda* accumulate within five to six centimetres of the soil surface. ISTA Rules (2010) recommend the use of KNO_3 for breaking dormancy of grass seeds. The pre-treatment of *D. nuda* seed with KNO_3 also increased the germination significantly but only in combination with relatively high constant temperatures. KNO_3 increased germination of *D. sanguinalis* where mean germination of 99% was achieved and dormancy induced by caryopsis covering structures and the pericarp was successfully decreased (Gallart et al., 2008). The positive effect of KNO_3 on germination of seed has been linked with an osmotic effect that enhances water and oxygen uptake by the embryo and a nutritional effect on protein synthesis (Gallart et al., 2008). Maize yield can be correlated with

42

the amount of nitrogen available in soil and producers will amend their fertilizer programmes accordingly. Enhancing nitrogen in soil may therefore stimulate germination of *D. nuda* seed when high soil temperatures prevail.

Soaking freshly matured *D. nuda* seed for 24 h in water significantly increased germination especially under constant temperature of greater than 25 °C. Pre-soaking or priming of seed with water over a period of time is not directly involved in breaking dormancy, but has rather an effect on the germination process itself (Biswas et al., 1978; Gallart et al., 2008). Naturally occurring inhibitors could be removed or washed out, initiating the germination process. Biswas et al. (1978) also found that certain enzyme activities that are beneficial for the germination process increased when soaking seed in water. Improved germination of pre-soaked *D. nuda* seed may be due to the removal of putative inhibitors, the decrease of mechanical constraints, a change in permeability of covering structures or a combination thereof (Baskin and Baskin, 2004; Gallart et al., 2008).

The heat pre-treatment of *D. nuda* seed yielded poor germination for both stored and freshly matured seed, except where stored seed was pre-chilled for 3 months. After-ripening of seed at 50° C for longer than 14 days increased germination of *D. ischaemum* (Schreb.) Muhl. (smooth crabgrass) and *D. sanguinalis* significantly (Taylorson and Brown, 1977). The short exposure of *D. nuda* seed to 60° C (only 24 h) was perhaps not long enough to break existing dormancy and increase germination. Although pre-chilling of *D. nuda* seed increased germination and can possibly break dormancy (Toole and Toole, 1941) the associated mechanisms/processes involved in the germination process was deemed beyond the scope of this study.

Although *D. nuda* seedlings emerged faster from within the first three centimetres of soil and were larger compared with the later emerging seedlings, the effect on seed production was not measured. The effect on plant growth and seed production can also be due to the longer growing period of first emerging plants and better environmental conditions

43

earlier in a growing season. Reproductive traits and seed production of *D. sanguinalis* were significantly influenced by time of emergence where plants emerging first had greater seed production than those emerging later (Galart et al., 2008).

Digitaria nuda emerged faster and grew better in clay loam soil, but showed very little emergence from a depth of 6 cm below the soil surface. According to Halvorson and Guertin (2003) *D. sanguinalis* can be found in nearly every soil type but grows better in sandy loam soils than clay soils with no emergence deeper than 6 cm. The decrease in emergence from deeper soil depths is mostly due to limited light, smaller seed size and also the gaseous environment and soil gas permeability (Benvenuti, 2003; Chauhan and Johnson, 2008a, 2008b). Benvenuti (2003) also found that soil physical properties play a major role in annual germination and emergence of weed seeds. Seed emergence was less prominent in sandy soil when compared with clay soil, and they concluded that clay soils showed better pedological conditions to accumulate certain weed seeds in a soil bank. Although significance between soil types was established in our study, severe infestations of *D. nuda* were observed in the previously mentioned maize-producing areas that consisted mostly of sandy soils with low clay content. Although *D. nuda* prefers clay soil, it has the ability to germinate and emerge successfully in sandy to sandy loam soils.

Effective seed germination is a key factor in the establishment of grass weed populations in crop production systems and is regulated by several factors. This study showed germination requirements to differ between related crabgrass species and to be very specific. Determining the effect of different factors influencing the germination ecology of a weed species, can assist in predicting flushes in emergence, thereby allowing for better timing of control practices. Constant high temperatures stimulated germination of *D. nuda* as has been reported for *D. sanguinalis* (Moreno and McCarty, 1994). In our study *D. nuda* germinated better than 50% at fluctuating 30/15 °C suggesting that season-long germination is possible especially in most maize producing areas where temperatures range between 15 and 35 °C.

Most studies on grass emergence indicated that more than 70% of seeds will germinate on the soil surface within the first year of seed shedding. Results from this study indicated that emergence of *D. nuda,* as with many other grass weed species, declined with increasing burial depth. This implies that rather shallow soil cultivation would be required, which might even be acceptable in cropping systems where minimum tillage is practiced. Subsequently, timely application of herbicides POST will be necessary to control late emerging seed from existing seed banks or dormant seed from previous seasons.

References

Aguyoh, J.N., Masiunas, J.B., 2003. Interference of large crabgrass (*Digitaria sanguinalis*) with snap beans. Weed Science, 51:171-176.

Barkworth, M.E., Capels, K.M., Long, S., Piep, M.B., 2003. Flora of North America. Vol 25. Magnoliophyta: Commelinidae (in part): Poaceae, Part 2. NY Oxford, Oxford University Press.

Baskin, J.M., Baskin, C.C., 2004. A classification system for seed dormancy. Seed Science Research, 14:1-16.

Benvenuti, S., 2003. Soil texture involvement in germination and emergence of buried weed seeds. Agronomy Journal, 95: 191-198.

Biswas, P.K., Devi, A., Riy, P.K., Paul, K.B., 1978. Enzyme activity in dormant and nondormant large crabgrass (*Digitaria sanguinalis*) seeds following hydration. Weed Science, 26:90-93.

Botha, C., 2010. Common weeds of crops and gardens in Southern Africa. Agricultural Research Council / Syngenta Pty. LTD., Business Print Centre, Pretoria, South Africa. 384 p.

Bromilow, C., 2010. Problem plants and alien weeds of South Africa. 3rd ed. Briza Publications, Pretoria, South Africa. 424p.

Brown, R.F., Mayer D.G., 1988. Representing cumulative germination. 2. The use of weibull function and other empirically derived curves. Annals of Botany, 61:127-138.

Chauhan, B.S., Gill, G., Preston, C., 2006. Influence of environmental factors on seed germination and seedling emergence of Oriental mustard (*Sisymbrium orientale*). Weed Science, 54:1025-1031.

Chauhan, B.S., Johnson, D.E., 2008a. Germination ecology of goosegrass (*Eleusine indica*): an important grass weed of rainfed rice. Weed Science, 56: 699-706.

Chauhan, B.S., Johnson, D.E., 2008b. Germination ecology of southern crabgrass (*Digitaria ciliaris*) and India crabgrass (*Digitaria longiflora*): Two important weeds of rice in the tropics. Weed Science, 56: 722-728.

Chauhan, B.S., Johnson, D.E., 2009. Germination ecology of spiny (*Amaranthus spinosus*) and slender amaranth (*A. viridis*): Troublesome weeds of direct-seeded rice. Weed Science, 57:379-385.

Chikoye, D., Manyong, V.M., Ekeleme, F., 2000. Characteristics of Speargrass (*Imperata cylindrica*) dominated fields in West Africa: crops, soil properties, farmer perceptions and management strategies. Crop Protection, 19:481-487.

Dias, N.M.P., Pereira, M.R.D.B., Lopez-Ovejero, R.F., Christoffoleti, P.J., Barela, J.F., Tornisielo V.L., 2005. Population dynamics of *Digitaria* spp. submitted to selection pressure by herbicides in sugarcane crop. Journal of Environmental Science and Health, B40:21-28.

Forcella, F., Wilson, R.G., Renner, K.A., Dekker, J., Harvey, R.G., Alm, D.A., Buhler, D.D., Cardina, J., 1992. Weed seedbanks of the U.S. cornbelt: Magnitude, variation, emergence and application. Weed Science, 40:636-644.

Fu, R., Ashley, R.A., 2006. Interference of large crabgrass (*Digitaria sanguinalis*), redroot pigweed (*Amaranthus retroflexus*) and hairy galinsoga (*Galinsoga ciliate*) with bell pepper. Weed Science, 54:364-372.

Gallart, M., Verdú, A.M.C., Mas, M.T., 2008. Dormancy breaking in *Digitaria sanguinalis* seeds: the role of the caryopsis covering structures. Seed Science and Technology, 36: 259-270.

Gardner, D., 1996. Crabgrass (Digitaria spp.) taxa. Agronomy 517: Weed biology and ecology. http://www.agron.iastate.edu/~weeds/weedBiolLibrary/u4crab1.html

Grabandt, K., 1985. Weeds of crops and gardens in Southern Africa. A Ciba-Geigy production. Seal Publishing, Johannesburg, South Africa.

Ghorbani, R., Seel, W., Leifert, C., 1999. Effect of environmental factors on germination and emergence of *Amaranthus retroflexus*. Weed Science, 47:505-510.

47

Hartzler, R.G., Buhler, D.D., Stoltenberg, D.E., 1999. Emergence characteristics of four annual weed   species. Weed Science, 47:578-584.

Halvorson, W.L., Guertin, P., 2003. Factsheet for Digitaria sanguinalis (L.) Scop. U.S. Geological survey, Southwest Biological Science Center. University of Arizona.

Ismail, B.S., Chuah, T.S., Salmijah, S., Teng, Y.T., Schumacher, R.W., 2002. Germination and seedling emergence of glyphosate-resistant and susceptible biotypes of goosegrass (*Eleusine indica* [L.] Gaertn.). Weed Biology and Management, 2:177-185.

ISTA, 2010. International Rules of Seed Testing. Edition 2010. The International Seed Testing Association, Bassersdorf, Switzerland.

Jooste, J.W., Van Biljon, J.J., 1980. The competition of *Cyperus esculentus* with maize. Crop Production, 9:151-155.

Kim, T-J., Neal, J.C., Ditomaso, J.M., Rossi, F.S.A., 2002. A survey of weed scientists' perceptions on the significance of crabgrasses (*Digitaria* spp.) in the United States. Weed Technology, 16: 239-242.

King, C.A., Oliver, L.R., 1994. A model for predicting large crabgrass (*Digitaria sanguinalis*) emergence as influenced by temperature and water potential. Weed Science, 42: 561-567.

Kok, P.D.F., 1984. Studies on *Digitaria* (Poaceae). 1. Enumeration of species and synonymy. South African Journal of Botany, 3:184-185.

Kok, P.D.F., Robbertse, P.J., Van Wyk, A.E., 1989. Systematic study of *Digitaria* section *Digitaria* (Poaceae) in southern Africa. South African Journal of Botany, 55: 141-153.

Launert, E., Pope, G.V., 1989. Flora Zambesiaca. Vol. 10, Part 3. Ed. P. Goetghebeur and P. Van der Veken (*Digitaria* spp.). Management committee of contributors to Flora Zambesiaca.

Maguire, J.D., 1962.Speed of germination-aid in selection and evaluation for seedling emergence and vigor. Crop Science, 2:176-177.

Moreno, J.E., McCarty, L.B., 1994. Factors affecting crabgrass (*Digitaria* spp.) germination. Proceedings of Southern Weed Science Society, p.71 (Abstract).

Monks, D.W., Schultheis, J.R., 1998. Critical weed-free period for large crabgrass (*Digitaria sanguinalis*) in transplanted watermelon (*Citrullus lanatus*). Weed Science, 46:530-532.

Nishimoto, R.K., McCarty, L.B., 1997. Fluctuating temperature and light influence seed germination of goosegrass (*Eleusine indica*). Weed Science, 45:426-429.

Payne, R.W., ed. 2011. The guide to Genstat ®. Release 14, Part 2: Statistics VSN International, UK.

Saayman-Du Toit, A.E.J., Le Court De Billot, M.R., 1991. Patrone van opkoms van sekere onkruide in veldtoestande. South African Journal of Plant and Soil, 8:153-157.

Steinmaus, S.J., Prather, T.S., Holt, J.S., 2000. Estimation of base temperatures for nine weed species. Journal of Experimental Biology, 51: 275-286.

Taylorson, R.B., Brown, M.M., 1977. Accelerated after-ripening for overcoming seed dormancy in grass weeds. Weed Science, 25: 473-476.

Toole, E.H., Toole, V.K., 1941. Progress of germination of seed of Digitaria as influenced by germination temperature and other factors. Journal of Agricultural Research, 63: 65-90.

Webster, R.D., 1983. A revision of the genus *Digitaria* Haller (Paniceae: Poaceae) in Australia. Brunonia, 6: 131-216.

Wells, M.J., Harding, G.B. Balsinhas, A., Van Gass, B., 1980. A preliminary experiment in sampling agronomic weeds for a national survey. Proceedings of the third National weeds conference of South Africa. Eds. S Nesser and ALP Cairns. Cape Town A.A. Balkema Rotterdam.

Zhang, H., Irving, L.J., Tian, Y., Zhou, D., 2012. Influence of salinity and temperature on seed germination rate and the hydrotime model parameters for the halophyte, *Chloris virgata*, and the glycophyte, *Digitaria sanguinalis*. South African Journal of Botany, 78:203-210.

CHAPTER 3

A comparison between relative competitive abilities of naked crabgrass *(Digitaria nuda* Schumach.) and large crabgrass (*D.sanguinalis* (L.) Scop.) in two soil water regimens

Abstract

The competitive ability of large crabgrass has been studied but is unknown for the closely related naked crabgrass also present in maize fields in South Africa. Consequently, comparative trials were done to determine the aggressiveness and level of competitiveness of both grass weeds under two watering regimes. A replacement series design was used in which naked crabgrass and large crabgrass were grown in five combinations of the two species (4:0, 3:1, 2:2, 1:3 and 0:4). Two levels of water treatments (a wet and dry soil profile) commenced after seedling establishment and were maintained until trial termination. Above- and below-ground biomass production, as well as tiller and panicle numbers were determined at the end of the trial. Competitive indices i.e. competitive ratio (CR), aggressivity index (AI), relative yield (RY), relative yield total (RYT) and relative crowding coefficient (RCC) were calculated for dry mass of root, shoot and total biomass. Water stress decreased the number of tillers and panicles of large crabgrass significantly in monoculture and treatment combinations. Total biomass of naked crabgrass in monoculture was greater compared to large crabgrass. Seed mass of large crabgrass was significantly (> 58%) higher in monoculture and treatment combinations. The AI was positive for naked crabgrass with regard to root mass and positive for large crabgrass with regard to shoot mass. Naked crabgrass was more competitive in the wet soil profile (CR = 1.88), while large crabgrass was more competitive in the dry soil profile (CR = 2.02). When in full competition (2N:2S) naked crabgrass and large crabgrass were equally competitive with regard to root, shoot and total biomass. The RY and RYT values were close to one, indicating that both species are making the same demands for resources. The RCC values also did not differ between species for all

biomass parameters. Strong competition between naked crabgrass and large crabgrass existed when grown in mixtures, whereas equal competitiveness was observed when planted in equal proportions. The aggressivity and competitiveness of naked crabgrass manifested in the root system, as opposed to the shoots of large crabgrass.

3.1 Introduction

Most *Digitaria* species occurring in South Africa are perennial grasses, occurring naturally or in cultivated pastures; are mostly palatable and provide good grazing. Only four species are regarded as grass weeds of importance in crops and include *Digitaria sanguinalis* (L) Scop. (large crabgrass), *D. ciliaris* (Retz.) Koeler (Southern crabgrass), *D. velutina* (Forssk.) Beauv. (velvet crabgrass) and *D. nuda* Schumach (naked crabgrass) (Botha, 2010; Van Oudtshoorn, 2009). These grass weeds are closely related in morphology and can only be distinguished from each other on minor taxonomic characteristics as discussed in Chapters 1 and 2. Therefore, producers have generally identified these grass weeds indiscriminately as large crabgrass, at least for the purpose of making herbicide decisions. Maize and sugar cane are regarded as two of the most economically important crops in South Africa and several studies listed large crabgrass as one of the most important grass weeds to cause yield losses in these crops (Dias et al., 2005; Jooste and Van Biljon, 1980; Kim et al., 2002). However, a lack of references to establish the weed status of the other, more unknown *Digitaria* species is of great concern since producers noted an increase in *Digitaria* species and tolerance to herbicide applications (See Chapters 4 and 5) in the central maize producing areas of South Africa. Although large crabgrass is still regarded as the dominant *Digitaria* species in most maize producing areas, naked crabgrass has been identified at increasing frequencies and its potential competitive ability to maize is unknown.

Related species often differ in their growth rate and ability to compete with crops for the availability of water, nutrients and light, especially when some of these resources are

51

limited (Aminpahah and Javadi, 2011; Souza et al., 2012). The competitive ability of species is mostly genetically controlled, but can also be a function of many characteristics resulting in some species utilizing limiting resources more effective (Karim, 2000). Several methods and designs are available to study the interference and the outcome of competition effects of weeds on crops and the interaction between coexisting species (Gibson et al., 1999; Snaydon 1991). However, much debate and controversy exist for almost all the methods and designs used to study plant interactions and weed-crop competition effects (Freckleton and Watkinson, 2000; Weigelt and Jolliffe, 2003). Experimental biases and limitations of designs mostly include and emphasize the effect and importance of plant density, size of target species and the time of data collection when studying the complexity of species coexistence and weed-crop competition (Jolliffe, 2000).

One of the most widely used and studied designs to determine and investigate interactions between two species is the replacement series design (Jolliffe, 2000; Snaydon, 1991). Harper (1977) as well as Cousens and O'Neill (1993) stated that the replacement series can generate valuable information when comparing the outcome of competition and to establish the magnitude of competition between two species. Although not without limitations, this design can provide insight on the interactions (or competition) between individual species, when there is shared requirements for a specific limiting resource that can lead to a reduction in the performance of one or both species (e.g. biomass allocation, growth rate and reproduction). The replacement series design consists of two components (i.e. species or genotypes) in their respective pure stands (monocultures) and with mixtures formed by substituting one component for that of the other so that the total number of plants per unit area stays constant (Snaydon, 1991). This design is therefore most suitable to determine the competitiveness of two species and the relative effects of interference within and between species (Radosevich, 1987) as closely related as large and naked crabgrass.

Several indices to interpret and quantify interference or competitiveness between species have been described (Weigelt and Jolliffe, 2003). The selection of indices should be

52

experiment specific and may have an important bearing on the interpretation of results. The specificity and clarity of meaning, as well as the mathematical and statistical properties should be taken into account, for only certain indices can be used successfully in a replacement series design (Snaydon, 1991; Weigelt and Jolliffe, 2003). Understanding the competitive and aggressive ability of large crabgrass and naked crabgrass can provide useful information for control purposes to be included in an integrated weed control program where one or both of these species can occur. The aim of this study was to determine the relative competitive abilities of large crabgrass and naked crabgrass based on their vegetative growth and biomass production in a replacement series design.

3.2. Materials and methods

3.2.1. Plant material and growth conditions

Seed of naked crabgrass and large crabgrass was sampled as described in Chapter 2 and stored at 15°C in air-tight plastic containers until commencement of trials. Seeds of both species were separately planted in seed trays and placed in the greenhouse to germinate. The soil used for germination in seedling trays and replacement series experiments was a sandy loam soil with 16% clay, 79% sand and 5% silt. Prior to planting the grass seeds of the replacement series, soil was sterilized with methyl bromide, sieved and placed in the respective seedling trays and square asbestos pots (360 x 360 x 360 mm) with drainage holes in the bottom for the replacement series trial. Grass seedlings were watered daily and the respective species were transplanted to the asbestos pots when two true leaves were visible (leave collar visible). Greenhouse conditions were 15/30 °C, 10h dark/ 14 h light to simulate natural growing conditions for both grass weeds. All pots received 500 ml water daily after transplanting for one week until grass seedlings were established in all the treatment combinations.

3.2.2. Species combination design

A replacement series experimental design was used with the respective grass weeds grown at a density of four plants per pot, simulating 33 grass seedlings m^{-2}. Naked crabgrass and large crabgrass were transplanted on 29 January 2013 in five treatment combinations at proportions of 100:0, 75:25, 50:50, 25:75 and 0:100. Actual plant numbers per pot for each treatment combinations were 4:0, 3:1, 2:2, 1:3 and 0:4, respectively. Grasses were planted in a rectangular pattern, spaced evenly apart from the middle of each pot. Treatments were completely randomized per replicate and all treatment combinations were replicated eight times in each water regime as well. The trial was maintained until maturity of grasses when leaves started to die off, 55 days after planting (DAP).

3.2.3. Water regimens

Two watering regimes were established in the replacement series experiment and consisted of well watered pots where water was not a limiting resource (wet soil profile) and a second regime where water availability was limited (dry soil profile). The establishment of the water regimes commenced one week after transplanting grass seedlings and soil profiles were maintained for the duration of the trial. Soil water content (SWC) was measured using a Decagon ECH$_2$O check hand-held meter (SWC measured in volume percent, cm.m^{-1}). Decagon 10HS (20cm in length) probes were positioned and buried in the middle of each pot to measure the soil water content before watering of pots. The wet soil profile was kept at greater than 60% SWC and the dry soil profile at lower than 40% SWC. Actual watering volumes were adjusted as grasses matured and the dry soil profile usually received 50% less water than the wet soil profile to ensure low soil water availability.

3.2.4. Biomass sampling

Tillers and panicles were counted 55 DAP. Panicles (most seeds still intact) were separated for each plant per pot and each species, respectively. Above ground shoots were cut off at the soil surface. Roots were recovered from soil and carefully washed to remove excessive soil. Panicle, shoot and root dry mass were determined after drying at 60 °C for 48 h. Total biomass per species and for each treatment was calculated as the sum of panicle mass and tiller mass (shoots). The root: shoot ratio was determined for each treatment. Seed mass of a 100 seeds per species was determined and total seed mass was calculated as a function of panicle mass.

3.2.5. Competition indices

The various competitive indices used for competition trials is summarized by Weigelt and Jolliffe (2003); two indices for studying the intensity of competition (e.g. aggressivity index (AI) and competitive ratio (CR)) and one index to analyze the competition effect between species (e.g. relative yield (RY)) were accordingly calculated for this study. The relative crowding coefficient (RCC) was also calculated in order to compare the relative competitiveness of each species. All indices were calculated for root, shoot and total biomass per pot.

Aggressivity index (AI)

Aggressivity compares the relative biomass increase of species "a" with species "b" in a mixture and also measures the interspecies competition of the two components to their respective monocultures (Jolliffe, 2000). The AI was calculated in this study to determine the extent to which naked crabgrass and large crabgrass mixtures vary from their respective monoculture using the following equations:

For mixtures: $$AIab = \frac{DMYab}{DMYaa \; x \; Zab} - \frac{DMYba}{DMYbb \; x \; Zba} \qquad [3.1]$$

55

$$AIba = \frac{DMYba}{DMYbb \ x \ Zba} - \frac{DMYab}{DMYaa \ xZab} \qquad [3.2]$$

For monoculture: $\quad AIab = \frac{DMYab}{DMYaa} - \frac{DMYba}{DMYbb} \qquad [3.3]$

$$AIba = \frac{DMYba}{DMYbb} - \frac{DMYab}{DMYaa} \qquad [3.4]$$

where *DMYab* is the dry mass yield of shoot, root and total biomass production for species "a" (naked crabgrass) in mixture with species "b" (large crabgrass); *DMYaa* is the biomass of naked crabgrass in monoculture and *DMYbb* is the biomass for large crabgrass in monoculture; *Zab (d_a/d_{ab})* and *Zba (d_b/d_{ba})* are the sown proportions of naked crabgrass and large crabgrass, respectively.

Competitive ratio (CR)

This is another index to measure and compare the competitive ability of different plants and also to measure competitive changes within a given combination as well as to identify which plant characteristics are associated with competitive ability (Joliffe, 2000). CR was calculated using the equation:

For mixtures: $\quad \text{CR}ab = \frac{DMYab}{DMYaa} \Big/ \frac{DMYba}{DMYbb} \qquad [3.5]$

$$\text{CR}ba = \frac{DMYba}{DMYbb} \Big/ \frac{DMYab}{DMYaa} \qquad [3.6]$$

Relative yield (RY)

Relative yield explains the demands made by a species for resource(s) in limitation (Harper, 1977; Joliffe, 2000). Relative yield was calculated using the equation:

For mixtures: $\quad \text{RY}ab = \frac{DMYab}{DMYaa} \qquad [3.7]$

$$\text{RY}ba = \frac{DMYba}{DMYbb} \qquad [3.8]$$

56

Relative crowding coefficient (RCC)

The RCC determines the competitive ability of one species to obtain limiting resources when grown in a mixture with another species, compared to its ability to use those resources when grown in a monoculture. The RCC values were determined with total dry mass yield (DMY) using an equation adopted by Novak (1993):

RCC = $(((DMYa_{(75:25)}/DMYb_{(75:25)}$ + $(DMYa_{(50:50)}/DMYb_{(50:50)}$ + $(DMYa_{(25:75)}/DMYb_{(25:75)})/3$ / $(DMYa_{(100:0)}/DMYb_{(100:0)})$ [3.9]

3.2.6. Statistical analyses

The experimental design was a randomised block design. The treatment layout was a split-plot with whole plots the two water regimes (wet and dry soil profile) randomly allocated within each of the eight block replicates. The sub-plot treatments were five mixture ratios 4:0, 3:1, 2:2, 1:3, 0:4 of two species randomly allocated within each main plot. The measurements were subjected to appropriate analysis of variance (PROC GLM procedure) using SAS version 9.2 statistical software (SAS Institute, 1999). Shapiro-Wilk's test was performed on the standardised residuals to test for deviation from normality (Shapiro and Wilk, 1965). Means of significant effects were compared using Student's t-LSD (Least Significant Differences) at a 5% significance level (SAS Institute, 1999).

3.3. Results

3.3.1. Biomass production and allocation

The effects on dry weight by watering regimes and respective treatment combinations of naked crabgrass and large crabgrass are shown in Table 3.1.

57

Table 3.1. The effect of treatment combinations on panicle, seed, tiller, shoot, root and total biomass of naked crabgrass and large crabgrass in two watering regimes (wet and dry soil profile). [See ANOVA table C3.1]

Treatment ratio	Soil profile	Panicle mass[1a]	Seed mass	Tiller mass[b]	Shoot mass[c]	Root mass	Total biomass[d]
		Naked crabgrass					
		g.pot^{-1}					
4N:0S		3.25	1.11	23.17	26.42	7.65	34.07
3N:1S	Dry	2.70	1.10	17.29	22.56	6.08	28.63
2N:2S		2.00	0.90	11.81	13.81	3.47	17.28
1N:3S		0.72	0.24	4.79	5.51	1.55	7.06
4N:0S		4.49	2.21	26.38	30.87	5.08	35.95
3N:1S	Wet	4.58	3.17	25.52	30.09	4.83	34.92
2N:2S		1.99	0.83	11.03	13.02	3.15	16.17
1N:3S		1.08	0.52	7.21	8.28	1.59	9.88
		Large crabgrass					
0N:4S		3.98	2.97	15.30	19.29	6.84	26.13
1N:3S	Dry	3.23	2.75	13.21	16.44	4.97	21.41
2N:2S		2.64	2.89	13.25	15.89	4.12	20.01
3N:1S		1.00	0.89	4.14	5.14	1.45	6.59
0N:4S		4.94	4.35	20.39	25.33	5.90	31.23
1N:3S	Wet	4.67	5.25	21.83	26.49	4.96	31.45
2N:2S		3.04	2.74	11.79	14.83	2.92	17.74
3N:1S		1.22	1.47	5.88	7.10	1.31	8.41

[a]Panicle mass includes seed mass; [b]Tiller mass includes panicle mass; [c]Shoot mass is sum of panicle and tiller mass; [d]Total biomass is sum of shoot and root mass

The different treatment combinations are denoted throughout as naked crabgrass: large crabgrass (N:S). Although treatment combinations had a significant main effect on all biomass parameters, the treatment combination x species interaction had the greatest effect on all biomass parameters, except for the root:shoot ratio. Soil profile was not significant for biomass parameters. Panicle number (F=6.29; P=0.014) and seed mass (F=17.00; P<0.001) were the

only parameters that differed significantly between the two species. Root and shoot ratio (F=13.53; P<0.001), panicle (F=31.49; P<0.001) and tiller numbers (F=21.31; P<0.001) differed significantly between dry and wet soil profiles. All interactions were significant for panicle and tiller numbers (Table 3.2). The number of tillers differed significantly between species. Naked crabgrass (4N:0S) had on average four tillers more compared to large crabgrass (0N:4S). Tiller numbers did not differ significantly between the remaining treatment combinations. Large crabgrass had significantly less tillers (65% less) in the dry soil profile, while naked crabgrass had on average 14 tillers in both soil profiles. The same tendencies were observed for panicle numbers. However, not all tillers of naked crabgrass produced a panicle, while all tillers of large crabgrass did (Table 3.2).

Table 3.2. Panicle and tiller numbers of naked crabgrass and large crabgrass and their treatment ratio within a replacement series for each soil profile.

Treatment ratio	Naked crabgrass			Large crabgrass		
	Dry	Wet	Mean	Dry	Wet	Mean
	Tiller number per pot					
0N:4S	-	-	-	6.75	32.57	19.66
1N:3S	5.38	5.88	5.63	7.04	24.75	15.90
2N:2S	10.75	10.14	10.45	8.13	18.50	13.31
3N:1S	16.13	20.50	18.31	6.88	8.38	7.63
4N:0S	23.13	23.88	23.50	-	-	-
Mean	13.84	15.10		7.20	21.05	

LSD(Specie X Soil profile) = 2.14

LSD(Ratio X Specie) = 3.03

LSD(Ratio X Soil profile X Specie) = 4.36

	Panicle number per pot					
0N:4S	-	-	-	6.31	33.14	19.73
1N:3S	3.63	4.75	4.19	6.04	26.13	16.08
2N:2S	8.88	8.71	8.79	6.75	17.13	11.94
3N:1S	12.63	17.88	15.25	6.38	8.50	7.44
4N:0S	15.88	19.88	17.88	-	-	-
Mean	10.25	12.80		6.37	21.22	

LSD(Specie X Soil profile) = 2.18

LSD(Ratio X Specie) = 3.08

LSD(Ratio X Soil profile X Specie) = 4.28

The shoot mass per pot of naked crabgrass in monoculture was significantly (P<0.001) higher (22%) than that of large crabgrass in monoculture. At the 2N:2S mixture, shoot mass did not differ significantly and the lowest shoot mass was recorded at the 1N:3S and 1S:3N combination treatments (6 g.pot^{-1}). Large differences in seed mass between species and treatment combinations were observed. Seed of large crabgrass developed and matured much earlier than that of naked crabgrass and 100 seeds weighed 0.66 g and 0.40 g for the

60

respective species. Seed mass of large crabgrass in monoculture weighed 58% more than seed of naked crabgrass in monoculture. Seed mass at the 2N:2S also differed significantly between species with large crabgrass seed weighing 71% more. Root mass, however, was almost the same for both species in all the treatment combinations with the highest dry weight at 6.4 g in the monoculture treatments. Total biomass per pot was consequently the highest for naked crabgrass in monoculture followed by 3N:1S and 0N:4S combinations. The biomass at the 2N:2S combination however, did not differ significantly between the grass species (Figure 3.1).
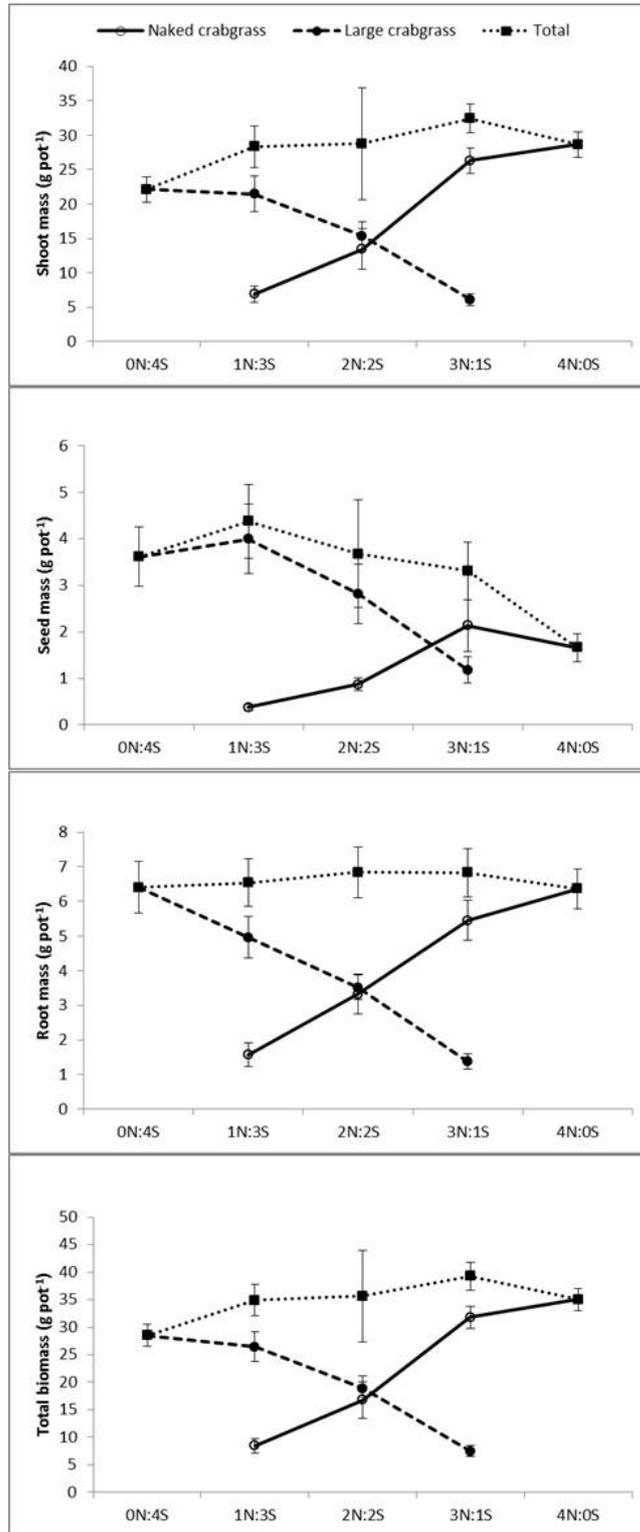
Figure 3.1. The root, shoot, seed and total biomass of naked crabgrass and large crabgrass and their combination in their various treatment combinations within a replacement series (mean of two soil profiles). Bars represent the standard errors of the mean.

The R:S ratio is shown separately for the respective grass species to illustrate their ability to invest biomass under stress conditions. Both grass species allocated more biomass to the root system in the dry soil profile for all treatment combinations except in the 2N:2S ratio. Naked crabgrass, however, showed significant differences between R:S ratios in both soil profiles and across the treatment combinations (except 2N:2S). The R:S ratio for both grass species was 0.31 and 0.22 for the dry and wet profile, respectively (Figure 3.2).
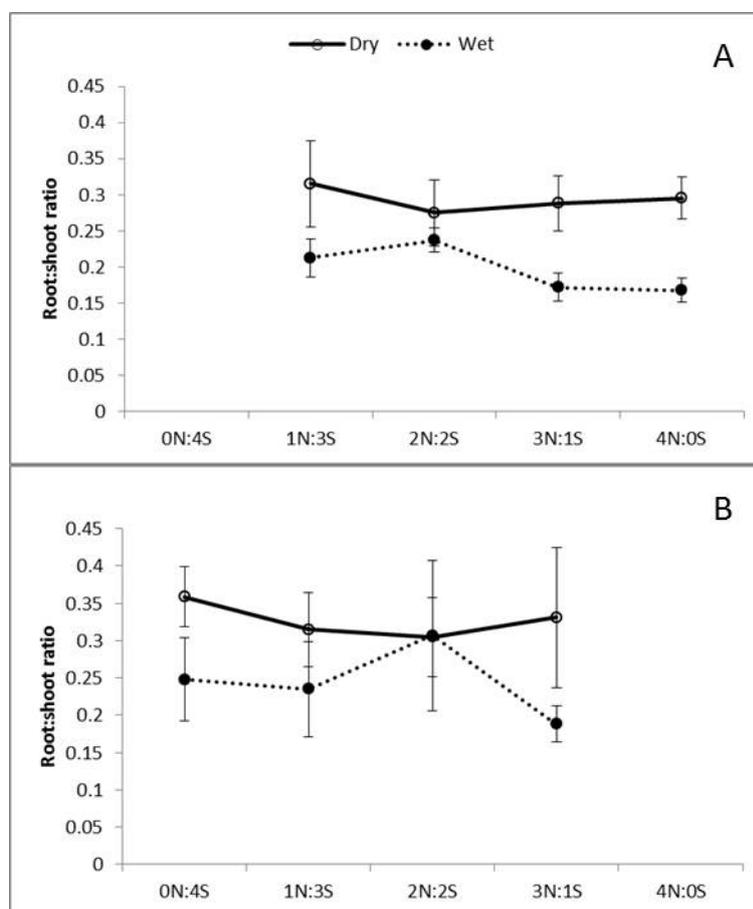
Figure 3.2. The root:shoot ratio of (A) naked crabgrass and (B) large crabgrass in their various treatment combinations within a replacement series for a wet and dry soil profile.

3.3.2. Competitive indices

If the AI=0, both species are equally competitive, while a positive value will signify dominance and a negative value will indicate the species that was dominated. A positive AI value was recorded for naked crabgrass root mass (0.3) and dominated large crabgrass (-0.3) significantly in the wet soil profile. In the dry soil profile the AI for root mass was however closer to zero (-0.07 and 0.07) for naked crabgrass and large crabgrass, respectively. The AI values for shoot and total biomass was not significantly influenced by the soil profile. The aggressivity of both species in the treatment mixtures is shown in Table 3.3 (AI values combined between soil profiles) for root, shoot and total biomass. Naked crabgrass dominated large crabgrass in the 3N:1S ratio for root, shoot and total biomass. Large crabgrass dominated naked crabgrass in the 1N:3S ratio only for shoot and total biomass. The AI in the 2N:2S ratio was equal to zero for all parameters indicating equal competitiveness between naked crabgrass and large crabgrass with regard to root, shoot and total biomass.

Table 3.3. Aggressivity index (AI) values based on root, shoot and total biomass of naked crabgrass and large crabgrass in their various treatment ratio within a replacement series

Treatment ratio	Root mass		Shoot mass		Total biomass	
	Naked crabgrass	Large crabgrass	Naked crabgrass	Large crabgrass	Naked crabgrass	Large crabgrass
3N:1S	0.29	-0.29	0.13	-0.13	0.23	-0.23
2N:2S	0.01	-0.01	-0.04	0.04	-0.02	0.02
1N:3S	0.05	-0.05	-0.23	0.23	-0.17	0.17

The CR was significantly influenced by the treatment combinations for root, shoot and total biomass. However, the interaction for treatment combination and species was highly

significant for root (F=90.69, P<0.001), shoot (F=134.89, P=0.001) and total biomass (F=189.12, P<0.001) and had the greatest effect on competitiveness (Table 3.4). Naked crabgrass was significantly more competitive than large crabgrass in the 3N:1S proportions with regard to root, shoot and total biomass and vice versa for large crabgrass in the 1N:3S proportion. Naked crabgrass and large crabgrass were equally competitive with regard to all biomass parameters in the 2N:2S proportion (Table 3.4). The interaction between soil profile and species was also significant for all parameters (Table 3.5: root mass: F=6.17, P=0.015; shoot mass: F=9.76, P=0.003; Total biomass: F=15.05, P=0.002). Naked crabgrass was significantly more competitive in the wet soil profile with regard to root and total biomass while shoot and total biomass indicated that large crabgrass was more competitive in the dry soil profile. The highest CR value for large crabgrass (2.02) was obtained for shoot mass in the dry soil profile and for naked crabgrass (1.88) for total biomass in the wet soil profile (Table 3.5).

Table 3.4. Competitive ratio (CR) values based on root, shoot and total biomass of naked crabgrass and large crabgrass in their various treatment ratio within a replacement series.

Treatment ratio	Root mass		Shoot mass		Total biomass	
	Naked crabgrass	Large crabgrass	Naked crabgrass	Large crabgrass	Naked crabgrass	Large crabgrass
3N:1S	3.57	0.29	3.12	0.33	3.47	0.28
2N:2S	1.13	1.12	1.04	1.27	1.06	1.22
1N:3S	0.39	2.99	0.30	3.69	0.31	3.52
LSD(Ratio x Species)	0.62		0.53		0.46	

Table 3.5. Competitive ratio (CR) values based on root, shoot and total biomass of naked crabgrass and large crabgrass in a wet and dry soil profile.

Soil profile	Root mass		Shoot mass		Total biomass	
	Naked crabgrass	Large crabgrass	Naked crabgrass	Large crabgrass	Naked crabgrass	Large crabgrass
Dry	1.55	1.76	1.27	2.02	1.34	1.93
Wet	1.85	1.17	1.70	1.50	1.88	1.42
LSD(Species x Soil profile)	0.50		0.43		0.38	

Relative yield was only significantly influenced by the treatment combinations for all biomass parameters for naked crabgrass (root mass: F=27.54; P<0.001; shoot mass: F=35.32, P<0.001; total biomass: F=38.78, P<0.001) and large crabgrass (root mass: F=18.19, P<0.001; shoot mass F=18.64; P<0.001; total biomass: F=26.37, P<0.001). The RY of naked crabgrass decreased with an increase in large crabgrass proportions and *vice versa*. The average RY of both species for root, shoot and total biomass per pot ranged between 0.62 and 0.70. When RYT=1, both species are making the same demands on the same

66

limiting resources; a RYT value <1 suggest a mutual antagonism and a RYT value >1 indicates that species make different demands on resources, avoid competition with each other or show a symbiotic relationship. No significant main effect (soil profile) or interaction effect (treatment combination x soil profile) was recorded for relative yield total (RYT) for any biomass parameters. The RYT for the 3N:1S ratio was however, slightly higher for all biomass parameters compared to the 1N:3S ratio. When in full competition with each other (2N:2S), the RYT values were close to one for all biomass parameters (Table 3.6).

Table 3.6. Relative yield (RY) and relative yield total (RYT) for root, shoot and total biomass of naked crabgrass and large crabgrass in their various treatment ratios.

Treatment ratio	Root mass			Shoot mass			Total biomass		
	Naked crabgrass	Large crabgrass	RYT[a]	Naked crabgrass	Large crabgrass	RYT	Naked crabgrass	Large crabgrass	RYT[a]
4N:0S	1.00	-	1.00	1.00	-	1.00	1.00	-	1.00
3N:1S	0.87	0.22	1.09	0.91	0.27	1.19	0.90	0.24	1.15
2N:2S	0.53	0.52	1.05	0.48	0.67	1.12	0.48	0.63	1.09
1N:3S	0.26	0.74	0.99	0.24	0.89	1.12	0.24	0.85	1.09
0N:4S	-	1.00	1.00	-	1.00	1.00	-	0.95	1.00

[a]RYT = Relative yield total

The RCC values calculated for root, shoot and total biomass of naked crabgrass and large crabgrass did not differ significantly between species or soil profiles. The RCC for naked crabgrass root, shoot and total biomass was 1.32, 0.98, and 1.29 (average = 1.19), and for large crabgrass 0.99, 1.31 and 1.23 (average = 1.17), respectively.

67

3.4. Discussion

Naked crabgrass stayed green for longer and matured slower compared to large crabgrass that showed senescence of older leaves at 55 DAP. Consequently naked crabgrass panicles were still green when the trial was harvested and seeds were not fully ripened (matured). Seed mass was conservatively measured, since large crabgrass produced seed much earlier than naked crabgrass, consequently shedding seeds sooner. Seed loss was, however, not taken into account. Competitive indices were therefore not calculated for seed mass, as to avoid wrong conclusions or to misinterpret competitiveness based on seed mass differences between the two grass species. Richmond et al. (2003) did, however, record an increase in large crabgrass seed production when in competition with perennial ryegrass (*Lolium perenne* L.).The deficit in soil water did not significantly decrease the dry biomass of naked crabgrass and large crabgrass grown in monoculture or in mixtures, indicating that both species can still grow competitively when drought situations prevail. Large crabgrass did, however, show a reduction of 16% in total biomass in the dry soil profile. Weed species grown under water stress showed changes in leaf morphology, phenology and biomass accumulation and subsequent resource use efficiency (Lucero et al., 2000; Xu et al., 2011). Substantial reductions in the number of tillers and panicles were recorded for large crabgrass, as compared to naked crabgrass. Similarly, competition studies done with rice and jungle rice (*Echinochloa colona* (L.) Link), as well as rice barnyardgrass (*Echinochloa oryzicola* Vasing) showed reduced tiller numbers of rice cultivars in full competition with grass weeds, leading to severe yield losses (Aminpanah and Javadi, 2011; Chauhan and Johnson, 2010). The inclination of naked crabgrass to produce the same number of panicles, regardless of soil moisture stress, and considerably later than large crabgrass, suggests that the former grass weed could be more tolerant to drought conditions with a possible increased competition effect/ability later in the growing season.

Root:shoot ratio is an important parameter to measure the extent of a plant's ability to invest biomass either in its shoots or root systems under stress conditions. Generally, most

68

plants will invest more biomass in the root system (higher R:S ratio) when water stress prevails, since the photosynthate will be allocated to root elongation (Wilson, 1988). Relatively stable R:S ratios in each proportion, except the 2N:2N, was due to the synchronous reduction in root and shoot biomass of naked crabgrass and large crabgrass. Similarly, Xu et al. (2011) recorded stable R:S ratios for the herbaceous grass *Bothriochloa ischaemum* (L.) between variable water stress regimes. Neither grasses allocated significantly more biomass to roots when soil water was limited, as would have been expected. This is in contrast with the general impression that grass species, having more fibrous root systems, will have increased R:S ratios when drought conditions prevail. In all the mixture combinations percentage biomass allocation to shoots and roots declined as the one species increased and the other one decreased, indicating that competitive ability between these species can be due to their morphological plasticity and similarity.

Competitive indices provided valuable information on the relative competitive abilities of naked crabgrass and large crabgrass as well as their levels of aggression. Although positive and negative AI values of biomass parameters were recorded for naked and large crabgrass, indicating dominance of a species, all values were close to zero.The greater the numerical value, the larger the difference between actual and expected biomass yield. Naked crabgrass and large crabgrass were therefore equally competitive, except where root mass of naked crabgrass dominated where water was unlimited. According to Xu et al. (2011), if an AI is greater with higher water availability, the intensity of competition may increase as the resource availability increases.

The CR index is frequently used in studies examining the effect of intercropping and is suggested to be a more useful index to quantify the competitive ability of plants (Weigelt and Joliffe, 2000; Xu et al., 2011). Higher CR values indicate greater competitiveness. The CR values (shoot and total biomass) of naked crabgrass and large crabgrass tended to increase as their respective proportions increased in a mixture. When in full competition, both grass weeds were equally competitive. The higher CR value of naked crabgrass with regard to root

mass, as opposed to shoot mass, indicated that its root competitive abilities were relatively higher than its shoot abilities, while the opposite was observed for large crabgrass. Large crabgrass in competition with perennial ryegrass allocated a greater proportion of resources to shoot mass; subsequently making a trade-off to increase seed production (Richmond et al., 2003). The lower CR values in the dry soil profile may indicate a decreased ability of naked crabgrass to optimally use the immediate water supply. Since the root and shoot competition was investigated simultaneously in this study the additive effect of root and shoot competition could not be determined (Cahill, 2002). The aggressiveness of both grass weeds depends therefore on the combined effects of root and shoot competition. The competition between plants and their respective effects on root and shoot biomass, separately or in combination, is rather a complex situation and conclusions should be made with great caution (Cahill, 2002; Kiær et al., 2013; Wilson, 1988). It is therefore rather safe to conclude that the interaction between root and shoot competition between plant species may not exclusively be a species specific trait. The effect of available resources, environmental conditions and density, size and position of neighboring plants can also influence this complex interaction (Cahill, 1999; 2002). According to Weigelt and Jolliffe (2003) the RCC index is only valid when two species are mixed in equal proportions. The RCC did not differ between naked crabgrass and large crabgrass, also indicating equal competitiveness.

Two of the most widely used indices for measuring competition in a two species mixture design are RY and RYT (Weigelt and Joliffe, 2000) which compare plant performances in mixtures and monocultures. The RYT is an advantageous tool to evaluate the complementary use of resources by two species and to quantify the extent to which a species in mixture capture more resources or use the available resources more effectively than monoculture (Connolly, 1987). When two plant species compete fully for resources, the expected RY values will be 0, 0.25, 0.50, 0.75 and 1.00, with the corresponding mixtures of 0:4, 1:3, 2:2, 3:1 and 4:0. The RY and RYT values did not differ significantly from these expected values except for a few ratios and both species shared the resources and competed

with similar abilities (Harper, 1977). Since naked crabgrass and large crabgrass are closely related, different demands for resources are highly unlikely. According to this study these two grass weeds can therefore, avoid competition, compete with similar abilities or have a symbiotic relationship with regard to allocation of biomass when growing in the same area (Lodge et al., 2000).

An ongoing debate exists in literature between the advantages, disadvantages and limitations of experimental designs for greenhouse studies and to determine and quantify the competition effect of plants with various competitive indices (Firbank and Watkinson, 1985; Freckleton and Watkinson, 2000; Gibson et al., 1999; Jolliffe, 2000, Oksanen et al., 2006; Snaydon, 1991; Weigelt and Joliffe, 2000). The replacement design was, however, chosen for this study since the aim was simply to determine the competitiveness between closely related grass weed species with regard to biomass accumulation and allocation. Most of the comments with regard to the use of the replacement design centers on the size effect of target plants and density of monoculture and mixture combinations to be used (Weigelt and Joliffe, 2000). Both grass weeds were of equal size and competition was established from the same vegetative stage. The limitations of the replacement design will, however, be apparent for the density aspect used in these experiments. It is not possible to extrapolate results from this study to grass populations of these two species under field conditions and follow-up trials will have to be done where the different densities of naked crabgrass and large crabgrass can be tested in the greenhouse and in field situations.

The debate on competitive indices is equally contentious and the selection of indices has to be chosen with regard to the aim of the study and the experimental designs. Weigelt and Jolliffe (2003) compiled and discussed more than 50 indices that were used in competition studies. According to their conclusions it is more beneficial to use more than one index for a study and it is imperative to acknowledge the limitations of these indices, which is strongly dependent on the experimental design used, and *vice versa*. All indices used in this study were appropriately used to elucidate the competitiveness between two closely related grass

species, since comparable results were recorded for the competitive abilities and aggressivity levels with regard to biomass (Table 3.7). This study demonstrated that there was strong competition between naked crabgrass and large crabgrass grown in mixtures, whereas equal competitiveness was observed when planted together (i.e. RYT ≥ 1). Water availability did not have a significant effect on biomass accumulation and allocation. The aggressivity and competitiveness of naked crabgrass manifested in the root system, as opposed to the shoots of large crabgrass.

Table 3.7. A summary of competitive indices for naked crabgrass and large crabgrass (averages over treatment combinations and soil profiles).

Biomass parameter	Competitive index[1]	Naked crabgrass	Large crabgrass	RYT[2]
Root mass	AI	0.11	-0.11	
	CR	1.70	1.47	1.02
	RY	0.66	0.62	
	RCC	1.32	0.99	
Shoot mass	AI	-0.13	0.13	
	CR	1.49	1.76	1.08
	RY	0.65	0.70	
	RCC	0.98	1.31	
Total biomass	AI	0.04	-0.04	
	CR	1.61	1.67	1.06
	RY	0.65	0.66	
	RCC	1.29	1.23	

[1]AI = Aggressivity index, CR = Competitive ratio, RY = Relative yield, RCC = Relative crowding coefficient;
[2]RYT = Relative yield total

CHAPTER 4

Comparative interference and competition status of naked crabgrass (*Digitaria nuda* Schumach.) and large crabgrass (*D. sanguinalis* (L.) Scop.) on maize.

Abstract

The competition effect of naked crabgrass and large crabgrass on maize planted on two soil types was studied in two greenhouse trials. The following maize: grass ratios, 1:0 (control), 1:2, 1:3, 1:4, 1:5 and 1:6 simulating densities of 17, 25, 33, 42 and 50 grasses per m^2 were established for both species. The rate of water use was calculated by the difference in soil water content (%) taken for 10 weeks after maize emergence. Plant height, dates of 50% silking and of ear initiation were recorded for maize. Grain weight and shoot mass of maize was determined at the end of the trial. Above-ground biomass of grass weeds were taken at 15 weeks after planting for large crabgrass trial and 20 weeks after planting for the naked crabgrass trial. A general linear regression model was used to determine the relationship between grass density, maize plant height, shoot mass and kernel weight. The relationship of maize yield and density of naked crabgrass and large crabgrass was described separately for each species and two soil types using the Cousens (1985) equation. The relationship between maize yield loss and total biomass of the respective grass species and maize was also fitted to the empirical model used by Kropff and Spitters (1991) to determine a damage coefficient (*q*). A negative linear correlation with increasing grass densities was recorded for all biomass parameters of maize for both grass weeds. Naked crabgrass reduced maize yield by 67 and 56% and large crabgrass by 79 and 82% on clay and sandy soil, respectively. Estimated yield loss of maize in control plots (weed-free) did not differ from observed yield losses for both grass species and soil type. Large crabgrass had the highest *q* value (3.1 and 4.2) on clay and sandy soils, compared to naked crabgrass (1.7 and 3.1). Both naked crabgrass and large

73

crabgrass should be effectively controlled since both species can cause significant yield losses of maize.

4.1 Introduction

Crabgrasses are one of the most common grass weed species found in several crops world-wide (Kim et al., 2002; Mitich, 1988;). In southern Africa, large crabgrass [*Digitaria sanguinalis*(L.)Scop.], naked crabgrass [*D. nuda* (Schumach.)] and Southern crabgrass [*D. ciliaris* (Retz.)] are commonly found in maize production areas due to the wide climatic conditions in which these grasses can survive and reproduce successfully (Botha, 2010; Bromilow, 2010). Most of these grasses are effectively controlled by PRE soil applied herbicides, but infestation levels can be severe later in the season when the residual activity of soil applied herbicides is no longer effective. Large crabgrass is reported to be an early season grass weed in maize production with 70% of a population emerging within 700 growing degree days (Dorado et al., 2009). An increase in the occurrence in naked crabgrass has been reported since 2008 in certain maize producing areas in South Africa and its effect on maize yield is unknown. Grass weeds tend to be more difficult to control in maize due to limitations in herbicide selections and with an increase in reduced tillage systems, grasses can reach higher infestation levels later in the season (Kobayashi and Oyanagi, 2005).

The effect of weed competition on various crops has been studied extensively but is still considered to be a complex field with several factors playing a role. There is an on-going discussion and debate in literature pertaining to different approaches (Gibson et al., 1999, Jolliffe, 2000; Rajcan and Swanton, 2001; Snaydon, 1991). The severity of weed competition and the manifestation in crop losses will depend on the time of emergence, dominant weed species, density of the infestation and the duration of the infestation period (Gibson et al., 1999; Rao, 2000). Similar growth habits and nutrient demands between crops and weeds will also increase the severity of competition. Maize, a C_4 plant, is considered to be an efficient

74

crop assimilating and utilizing nutrients optimally through various physiological processes (Rao, 2000). *Digitaria* species are also C_4 plants with similar requirements as maize, enhancing their competitiveness. Grain yield of maize, determined by kernel number per plant and kernel weight, is greatly influenced by stresses just before and during the silking stage (Cerrudo et al., 2012; Tollenaar, 1992). However, stress during the early seedling stages of maize has also been recorded to reduce grain yield significantly (Hall et al., 1992; Swanton et al., 1999).

Although the ability of large crabgrass to compete with crops has been well documented (Aguyoh and Masiunas, 2003; Monks and Schultheis, 1998), the effect on grain yield of maize has not been quantified in South Africa for *Digitaria* species. Very little research has also been done on naked crabgrass other than positive identification (Chikoye et al., 2000; Dias et al., 2005; Kok et al., 1989), comparative studies to other *Digitaria* species (Souza et al., 2012) and responses to various herbicides (Dias et al., 2005; Vieira et al., 2010). Consequently, the question amongst producers arises whether the more unknown naked crabgrass can cause yield losses in the same range as large crabgrass and if these species differ in their competition outcome effect on maize. The competitiveness of *Digitaria* species also manifest in their ability to grow in almost any soil type, by growing under stress conditions and by producing abundant seed (Kim et al., 2002; Mitich, 1988).

Several weed-crop models have been developed over the years to better understand factors influencing competitiveness of either one or numerous weed species on crops (Cousens, 1985, Kropff and Spitters, 1991). Various models including linear (Bauer and Mortensen, 1992), quadratic, sigmoidal (Zimdahl, 2004) and rectangular hyperbola (Cousens, 1985) have been developed but differ in their ability to describe the effect of weed competition on crops. Due to the complexity and difficulties to interpret results in field studies and mixed populations of weed species, it is often more valuable to determine the effect of weed species under controlled conditions (greenhouse trials) (Freckleton and Watkinson, 2000; Gibson et al., 1999). In this study a simple additive design was used to compare the outcome of the

75

competition effect and interference on crop growth between naked crabgrass and large crabgrass on maize, respectively. Since their morphology and vegetative growth are almost identical and not distinguishable in the seedling stage the competition effect of both species was determined in separate greenhouse trials. The aim of this study was therefore to distinguish between the competitiveness of large and naked crabgrass and to quantify the effect on crop development and grain yield of maize in two different soil types.

4.2 Materials and methods

The competition effect of different densities of large crabgrass and naked crabgrass on maize was determined in two separate pot trials in a greenhouse. The maize: naked crabgrass trial was planted on 26 July 2011 and harvested on 5 December 2011; the maize large crabgrass trial was planted on 16 May 2012 and harvested on 29 October 2012. Greenhouse conditions were 15/30°C, 10 h dark/ 14 h light conditions to simulate natural growing conditions for maize. Mature seed of large crabgrass was harvested at Cedara, (29°32'15.28" S, 30°16'09.11" E) KwaZulu-Natal and naked crabgrass seed was harvested at Wesselsbron, (26°26'30.69" S, 27°41'27.85" E) Free State Province. Seed was kept in air-tight plastic containers at 15 °C until commencement of trials. Two soil types namely a sandy clay-loam (36% clay, 59% sand and 5% silt) and a sandy loam soil (16% clay, 79% sand and 5% silt) were used to conduct the trials. Both soils were sterilized separately with methyl bromide, sieved and placed in square asbestos pots (360 x 360 x 360 mm) with drainage holes in the bottom. Collective soil samples from each soil type were taken prior to trial initiation and analysed (Appendix A: Table A.1). Soil in asbestos pots was watered prior to planting grasses and maize with app. 5 L until drainage was observed. Grass seeds were sown in seedling trays and seedlings were transplanted to asbestos pots when one true leaf was fully unfolded, eliminating the effect of different seedling sizes. The respective species were planted to obtain the following maize: grass ratios, 1:0 (control), 1:2, 1:3, 1:4, 1:5 and 1:6 simulating densities of

76

17, 25, 33, 42 and 50 grasses per m^2. The maize cultivar DKC78-35R was planted one week after grass seedlings to ensure competition from the seedling stage. Two maize seeds per container were planted in the centre of each pot of which one seedling was harvested at the fourth leaf stage for leaf analysis. Grasses were spaced evenly around the maize plant to ensure the same planting pattern for each ratio treatment. After planting, pots were initially watered with 500 ml daily until maize seedlings emerged and grass seedlings were established. The amount of water was adjusted to accommodate the growth stages of maize without water stress and a maximum of 5 L per pot was maintained prior to silking until maturity. Decagon 10HS (20 cm in length) probes were positioned and buried in the middle of each pot to measure the soil water content (SWC) with a Decagon ECH$_2$O check hand-held meter (SWC was measured in volume percent, cm.m^{-1}). Simultaneous watering of all pots was done at the beginning of the week (from Monday) and SWC was measured at the same time daily for five consecutive days (to Friday) to determine the rate of water use in each treatment ratio over time. The rate of water use was calculated by the difference in SWC (%) taken over five days for 10 weeks after maize emergence. Plant height of maize was determined in all treatments at weekly intervals until tasseling. Dates of 50% silking and of ear initiation were recorded for maize. The leaf opposite and below the ear of each maize plant in each treatment was sampled at tasseling for a second nutrient analysis (Leaves were pooled over replications for analysis purposes). Grasses were cut off at the soil surface when leaves started to senesce at 15 weeks after planting (WAP) for naked crabgrass and 20 WAP for large crabgrass. Shoots were dried at 60 °C for 48 h to determine dry mass. Ears of maize plants were hand harvested, shelled and weighed. After threshing total grain weight was determined and kernel moisture content was adjusted to 12.5%. Stems and leaves of maize plants (shoot mass) were cut off at the soil surface and dried at 60 °C until weight was constant. Total biomass of maize was the sum of shoot mass plus kernel weight.

4.2.1 Statistical analysis

Two randomised complete block design experiments were performed for each of the respective grass species with grass density and soil type as factors, replicated eight times per soil type.

The data on grass dry mass, days to 50% silking of maize, days to maize ear initiation and number of maize ears were tested for homogeneity of variances using Levene's test. In cases where there were strong evidence against homogeneity a weighted analysis of the observations were carried out separately for each grass species, using the inverse of the pooled variances of each soil type as weight. The Shapiro-Wilk test was performed to test for normality. Student's t-Least Significant Difference were calculated at the 5% level to compare treatment means for significant effects. All the analyses were done with using SAS v9.2 statistical software (SAS Institute, 1999).

The general linear regression model was used to determine significance (relationship) between increasing grass density, maize plant height, shoot mass and kernel weight using Genstat for Windows 15th edition (Payne, 2011). The nonlinear hyperbolic regression model was used to analyse the relationship between maize yield and grass density (Cousens, 1985). The relationship of maize yield and density of naked and large crabgrass was described separately for each grass species and two soil types using the Cousens (1985) equation to plot yield losses to the hyperbolic curve:

$$YL = \frac{Id}{(1+Id/A)} \qquad \text{[4.1]}$$

where *YL* = yield loss (%), *I* = yield loss as grass density approaches 0 (%), *A* = yield loss as grass density approaches infinity (%), and d = grass density. *A* was constrained not to exceed 100% (Cousens, 1985).

The hyperbolic yield curve (Cousens, 1985) was fitted to yield loss data (kernel weight per plant) to estimate yield loss in weed-free treatments (*Ywf*) and to compare it to observed yield losses (*YL*):

78

$$YL = Ywf[1 + 100(1 + \frac{Id}{Id/A)}] \qquad [4.2]$$

The relationship between maize yield loss and total biomass (dry mass) of the respective grass species (weed) and maize (crop) was also fitted to the empirical model used by Kropff and Spitters (1991). The parameter of L_w (share in total leaf area) was used to describe the total share in biomass of the respective grass species (Galon and Agostinetto, 2009):

$$Bs = \frac{Bw}{Bc+Bw} \qquad [4.3]$$

Where Bs = total share in biomass, Bw = biomass of weed species (shoots and panicles) and Bc = biomass of crop (shoots and kernels). The relationship between biomass and increasing grass density correlated similarly with the theoretical relationship between yield loss and leaf area of weeds demonstrated by Kropff and Spitters (1991). The one parameter model of Kropff and Spitters (1991) also provided an estimate of the relative damage coefficient (q) to determine the competitiveness of naked and large crabgrass against maize, using total share in biomass instead of leaf area index (Galon and Agostinetto, 2009; Lutman, et al., 1996):

$$YL = \frac{qBs}{1+(q-1)Bs} \qquad [4.4]$$

Significance of I, A and q parameter coefficients was determined using the 95% confidence limits to compare between grass species and soil types. Confidence limits that do not overlap are considered significant at the 5% significance level. The curve fitting program Statsoft (Table-curve 2D) for Windows version 5.01 was used to plot nonlinear models of both Cousens (1985) and Kropff and Spitters (1991) (Systat, 2002).

4.3. Results

Although maize growth up to maturity is not optimal in greenhouse studies due to the "potting effect", plants reached maturity and produced ears within the normal time frame of crop development in the grass-free control treatments. Maize took 130 days to reach maturity in the

79

naked crabgrass competition trial, and 160 days in the large crabgrass trial. Leaves of large crabgrass plants took longer to start senescing compared to naked crabgrass leaves. According to the soil analysis both soil types showed sufficient nutrient status for successful maize production. The optimal temperature for maize germination and emergence is between 20 and 30 °C and maize germinated within six days after planting. The soil water content of both soil types was kept greater than 60% to ensure sufficient soil water for both grasses and maize, ensuring grass density to be the measured competition effect (Werner, 2002).

Soil water content (mean over time and soil types) ranged between 54 and 58% with increasing naked crabgrass densities (F=8.60; P<0.001) compared to 49 to 54% with increasing large crabgrass densities (F=8.06; P<0.001). Soil type had a significant effect on SWC and was 3% lower on sandy soil compared with clay soil where naked crabgrass was in competition with maize (F=19.81; P<0.001). Soil water content was, however, 34% lower on sandy soils where large crabgrass competed with maize (F=2737; P<0.001). The interaction effect between grass density and soil for both grasses is shown in Figure 4.1.
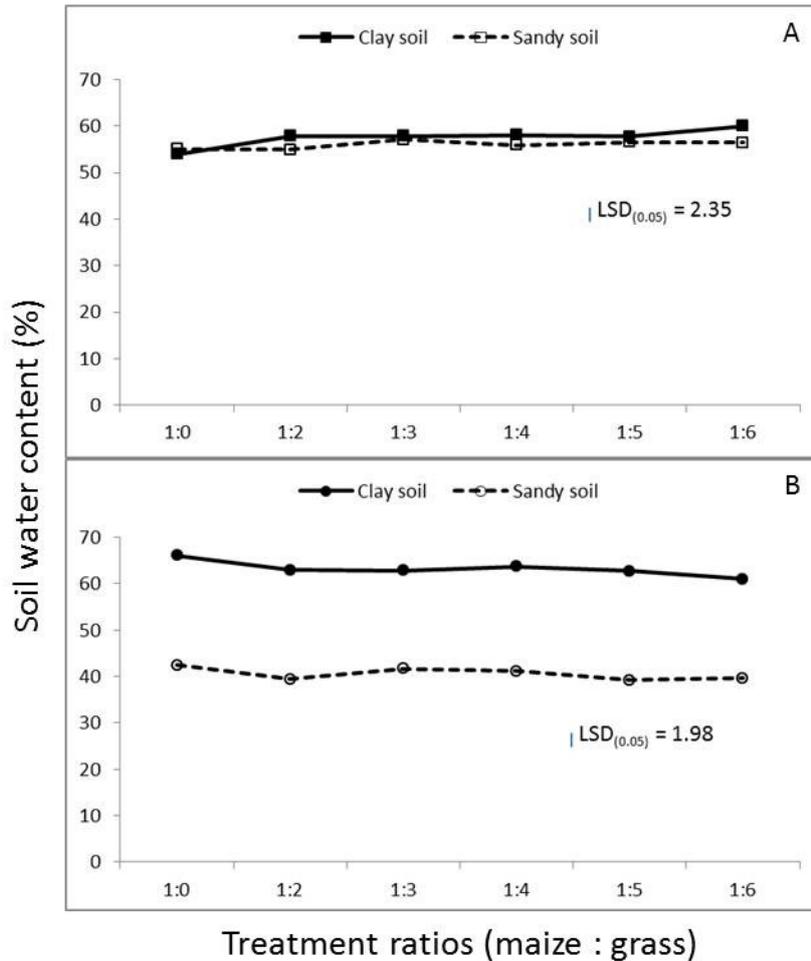
Figure 4.1. Soil water content (%) as effected by A) naked crabgrass and B) large crabgrass competition with maize over increasing grass densities. (LSD = Fishers unprotected at P=0.05)

Soil water content was significantly lower in sandy soils over all grass density treatments compared with clay soil where large crabgrass was in competition with maize (Figure 4.1 B and A). The rate of water use was not influenced by soil type and increased by more than 20% when naked crabgrass competed with maize (Figure 4.2 A). The rate of water use was, however, significantly influenced by soil type and was higher on sandy soils increasing by 9 and 18% on clay and sandy soil, respectively, when large crabgrass competed with maize (Figure 4.2 B).

81
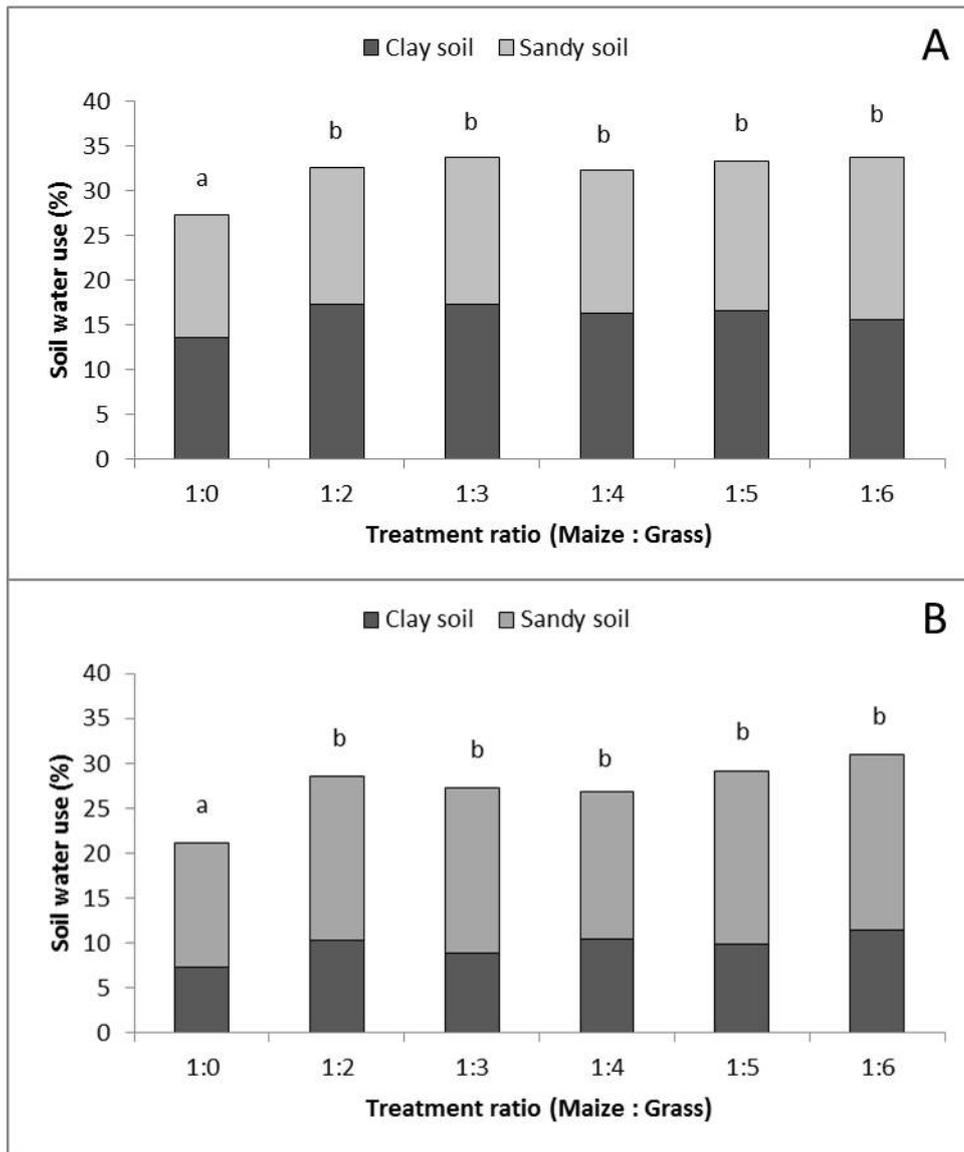
Figure 4.2. The contribution effect of A) naked crabgrassand B) large crabgrass on the rate of water use in competition with maize grown in two soil types. (Bars with the same letter do not differ significantly at P=0.05)

The critical nutrient levels in maize leaves have been documented in several studies (Elwali et al., 1985; FSSA, 2002) and maize leaf samples from the grass-free control treatments fell well within the limits of nutrients measured (Appendix A: Table A.3 and A.4). Nitrogen (N) in maize seedling leaves on sandy soil decreased by 15% with increased naked crabgrass densities, but no decrease was observed in mature maize leaves. Potassium (K) decreased by 32 and 20% in seedling and mature leaves of maize respectively as naked

82

crabgrass densities increased. Nitrogen levels did not differ in maize leaves (seedling or mature) on clay soil and only P and K decreased by 24 and 28%, respectively in seedling leaves as naked crabgrass densities increased. The only reduction of nutrients was observed in mature maize leaves occurred on sandy soil where the N level decreased by 35% as large crabgrass densities increased. Nitrogen levels decreased by 5 and 22% in seedling and mature maize leaves respectively as large crabgrass densities increased on clay soil.

Dry mass per naked crabgrass plant differed greatly between soil types and the average plant weighed 35% less on sandy soil compared to clay soil (Figure 4.3). The decrease in dry mass per naked crabgrass plant ranged from 37 to 18 g on clay soil and from 13 to 7 g on sandy soil with increasing grass densities. The difference in dry mass per plant between soil types was less prominent for large crabgrass and plants weighed 35 and 34 g on clay and sandy soil, respectively. Dry mass per large crabgrass plant decreased by between 35 and 17 g as grass densities increased.
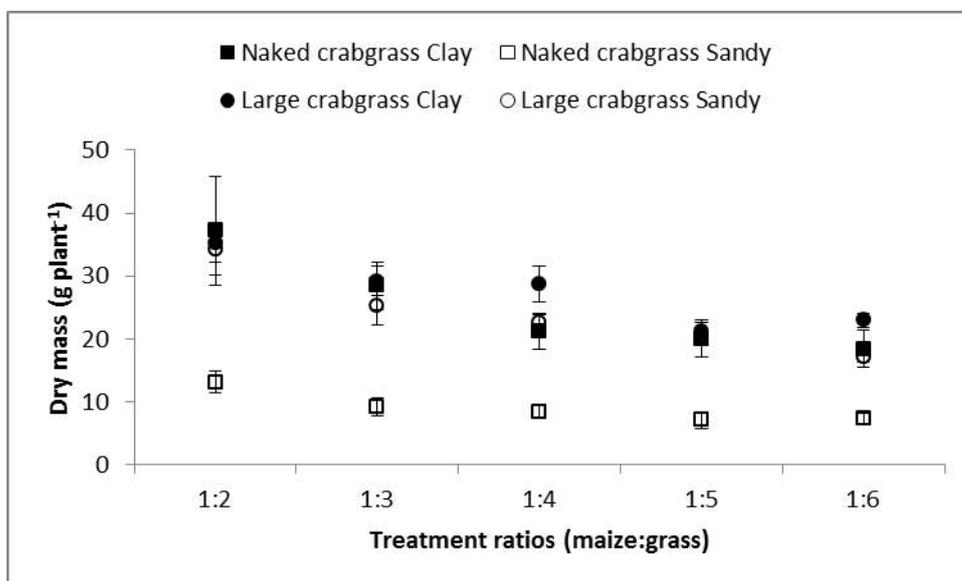
Figure 4.3. Effect of increased grass density on dry mass per plant for naked and large crabgrass grown on two soil types. (Vertical bars indicate standard error of the means)

83

A negative linear correlation with increasing grass densities was recorded for plant height, shoot mass and kernel weight of maize in competition with both grass species (Figure 4.4). Soil type only affected maize plant height significantly when in competition with large crabgrass; plant height was 9% lower on sandy soil. Maize plant height decreased more rapidly when in competition with naked crabgrass and was reduced with app. 6 cm for each increase in grass density. Naked crabgrass increased maize stunting up to 35%, while large crabgrass stunted maize only 5% (Figure 4.4 A and B). In contrast, maize shoot mass reduced more rapidly when in competition with large crabgrass compared to naked crabgrass (Figure 4.4 C and D). The highest decrease in maize shoot mass was recorded in competition with large crabgrass on sandy soil with a redcution of 25 g as large crabgrass densities increased to six grasses pot^{-1}. Maize shoot mass was reduced on clay soil by 62 and 51% when grass densities of naked and large crabgrass increased to six grasses pot^{-1} respectively. The decrease in maize kernel weight was more rapid for maize in competition with naked and large crabgrass on clay soil compared to sandy soil (Figure 4.4 E and F). The reduction in maize kernel weight ranged from 39 to 67% and from 49 to 82% for naked and large crabgrass, with an increase from two to six grasses pot^{-1} in clay soil. The same tendency was observed for kernel weight on sandy soil with increasing grass densities.
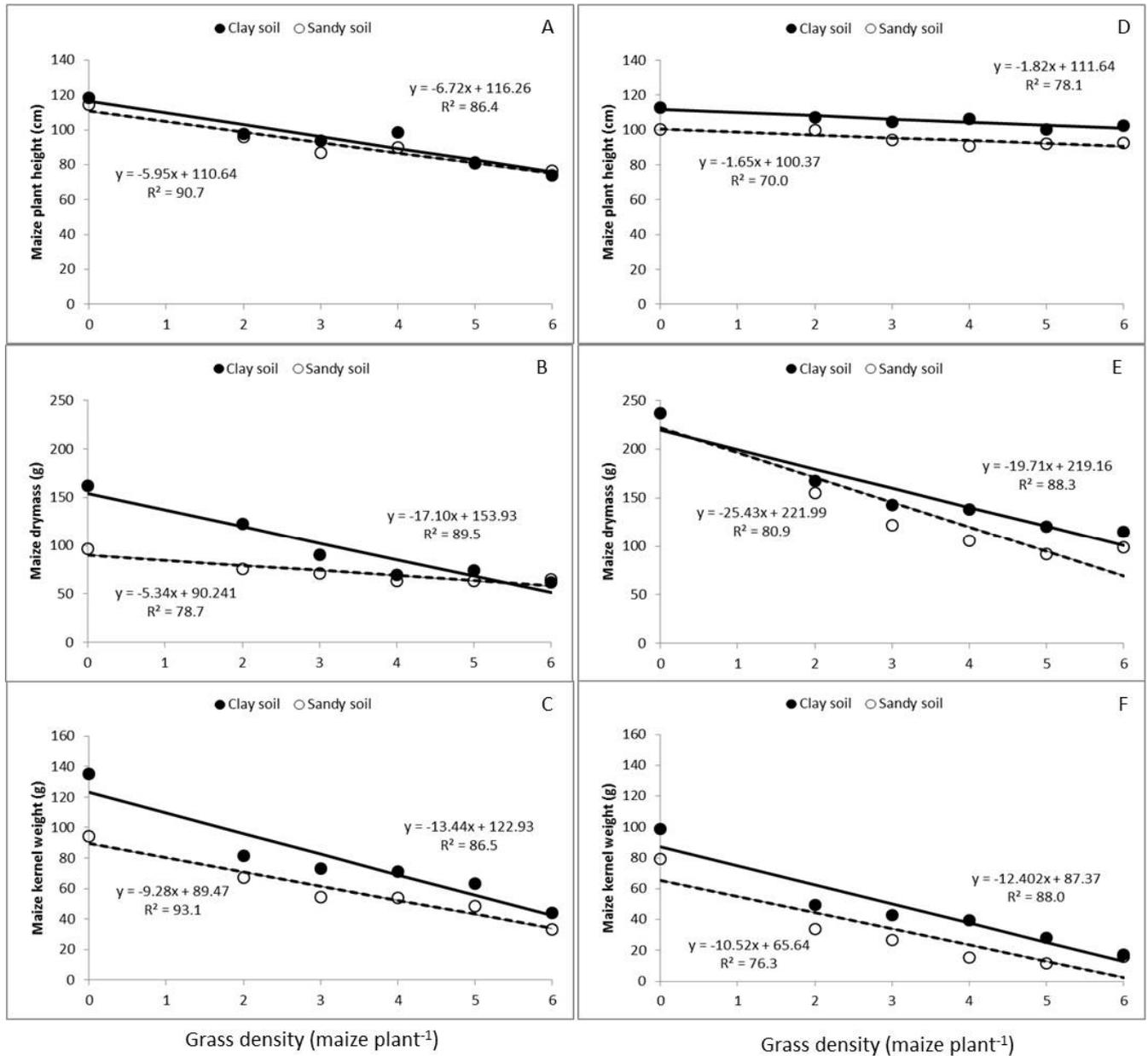
Figure 4.4. Plant height, dry biomass and kernel weight of maize as influenced by grass density of naked crabgrass (A, C, E) and large crabgrass (B, D,F) grown in two soil types. Linear regression lines were fitted to data, symbols are observed data (solid lines and symbols = clay soil and dashed lines and open symbols = sandy soil).

Maize kernel weight and percentage yield loss were dependent on soil type and grass density. The percentage yield loss was greater for maize in competition with large crabgrass compared to naked crabgrass on both soils (Figure 4.5 A and B). At a density of six grasses

85

per maize plant (simulating 50 grasses per m^2), maize yield was reduced by 67 and 56% respectively in competition with naked crabgrass on clau and sandy soil, while large crabgrass competition reduced yield by 79 and 82%, on the same two soils (Figure 4.5). The hyperbolic regression model (Eq. 4.1) described the relative competitiveness of naked and large crabgrass by the percentage of maize yield loss as the weed density approaches zero (*I*) and the percentage maize yield loss as the weed density approaches infinity (*A*) (Cousens, 1985). The *I* values of large crabgrass was 49 and 76% and for naked crabgrass 29 and 21%, on clay and sandy soil respectively. Large crabgrass was therefore more competitive than naked crabgrass on both soil types, also causing greater yield loss than the latter. Both *I* and *A* values, however, did not differ significantly between grass species and soil type (overlapping of 95% confidence limits). Maize kernel weight in weed-free pots was 135 and 94 g on the clay and sandy soils respectively in the naked crabgrass trial, while these figures were 99 and 79 g on the same soils in the large crabgrass trial (Table 4.1). The estimated yield loss in weed-free plots (*Ywf*) did not differ from the observed (*YL*) yield for both grass species and soil types (Table 4.1).

Table 4.1. Maize yield reduction in competition with naked and large crabgrass as described by parameter estimates (±SE) of the rectangular hyperbola regression model

Grass species	Soil type	Yield		Parameter estimates[a]		
		Observed	Estimated[b]	*I*	*A*	*q*
		g.plant^{-1}		%		
Large crabgrass	Clay	98.7(6.1)	97.0(8.0)	48.7(14.6)	99.9(15.5)	3.1(0.3)a
	Sandy	79.3(8.7)	76.4(10.1)	75.9(23.0)	99.9(10.6)	4.2(0.3)a
Naked crabgrass	Clay	135.2(8.1)	133.9(8.6)	29.0(8.2)	94.6(20.9)	1.7(0.1)b

				99.9(33.8)	3.1(0.3)a
Sandy	94.2(4.1)	92.3(6.7)	21.4(6.7)		

[a]*I* (slope) is the percentage yield loss as density approaches 0, *A* (asymptote) is percentage yield loss as density approaches infinity, *q* = damage coefficient determined with the equation $YL = qBs/1 + (q – 1)Bs$; *Bs* = total share in biomass. [b]Estimated maize yield in weed-free plots (*Ywf*) fitted to equation 4.4, $YL = Ywf [1+ (Id/100(1 + Id/A)]$; *YL* = Yield loss, *d* = grass density.
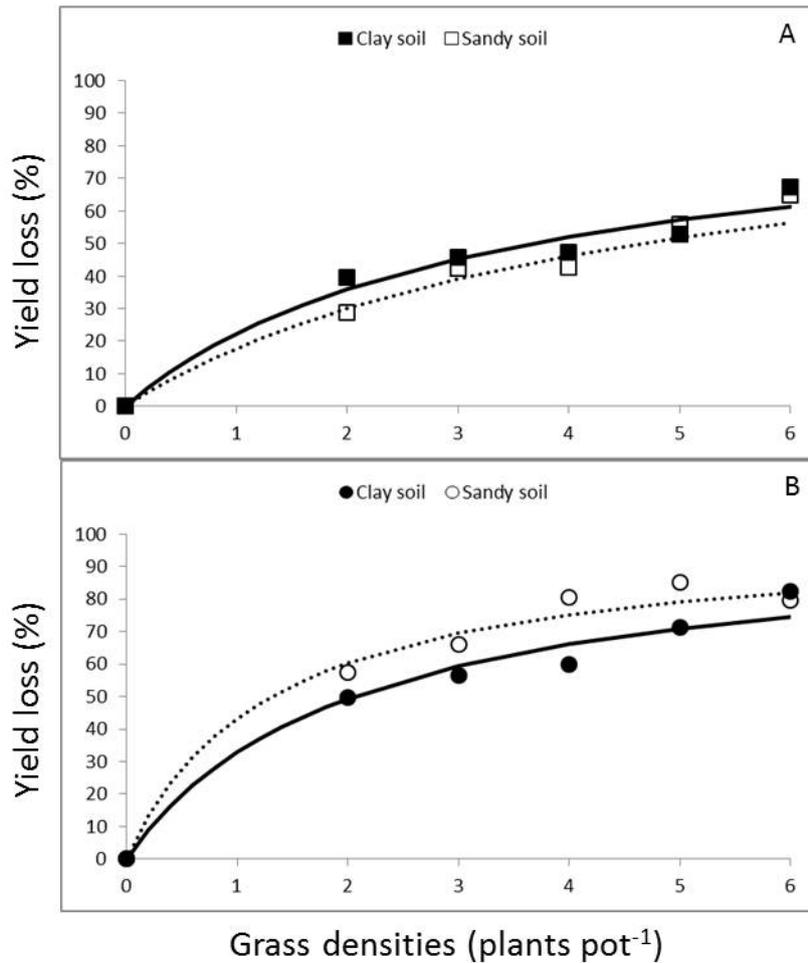
Figure 4.5. Relationship between maize yield loss and A) naked crabgrass and B) large crabgrass density in two soil types (open symbols = sandy soil, solid symbols = clay soil) fitted to a rectangular hyperbola regression model (Eq. 4.1) (Cousens, 1985). Solid and dashed lines are fitted regressions and the symbols are observed yield loss. The slope (*I*) is the percentage yield loss as density approaches 0 and the asymptote (*A*) is the percentage yield loss as density approaches infinity as presented in Table 4.1. (Coefficients of determination all > 0.96)

87

The derived values of total share in biomass fitted the empirical model of Kropff and Spitters (1991) and a damage coefficient could be estimated for both grass species on both soil types (Figure 4.6). The damage coefficient (q) for naked crabgrass differed significantly between soil type and was 1.7 and 3.1 on clay and sandy soil respectively. The higher q values for large crabgrass on both soil types (clay = 3.1 and sandy = 4.2) again indicated the greater competitiveness of this grass species and corresponded with the I-values from Cousen's (1985) model.
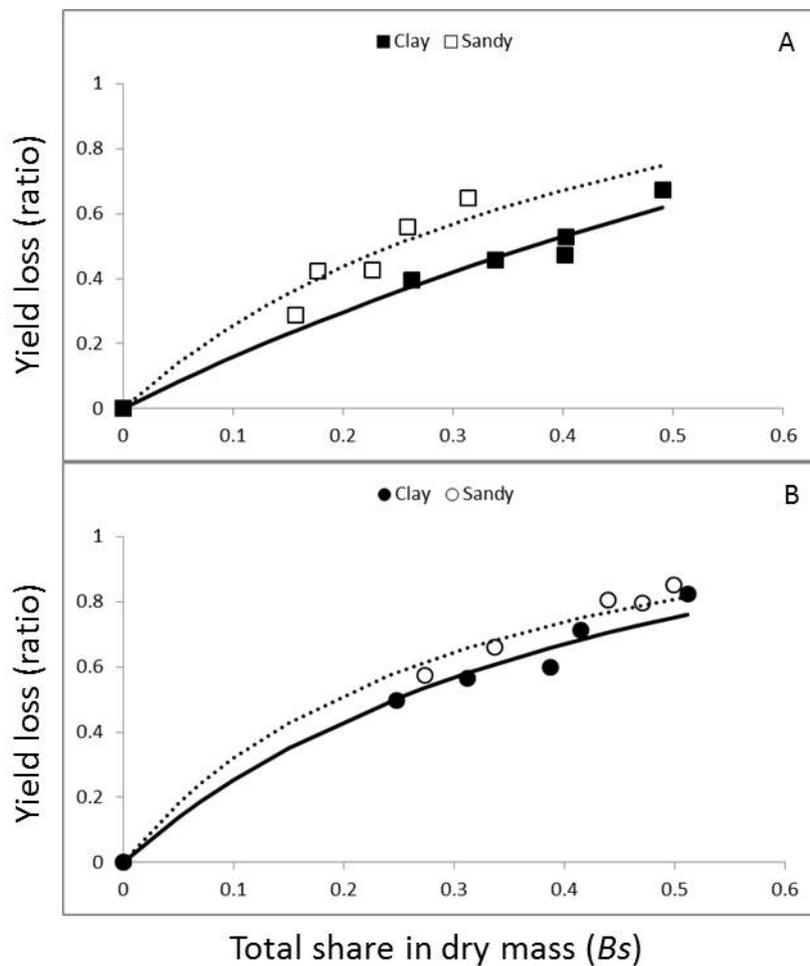
Figure 4.6. Percentage maize yield loss ratio as affected by total share of biomass (maize and grass) at maturity for A) naked and B) large crabgrass on both soil types (open symbols = sandy soil, solid symbols = clay soil). Solid and dashed lines are fitted to the regression model of Kropff and Spitters (1991) and the symbols are observed yield loss (Eq. 4.3 and 4.4). (Coefficient of determination all > 0.95)

88

Although both soil type and naked grass density influenced the number of days to 50% silking (soil: F=27.25, P<0.001; density: F=8.49, P<0.001), ear initiation (soil: F=56.59, P<0.001; density: F=9.32, P<0.001) and number of ears (soil: F=7.67, P=0.007; density: F=5.81, P=0.002) of maize plants significantly, soil type had the greatest effect (greater F-values). In contrast, only large crabgrass density had a significant effect on the above mentioned maize parameters and the effect of soil type was negligible (F-values lower than three). The number of days to 50% silking of maize increased between two to10 days when in competition with naked crabgrass and between five to 13 days in competition with large crabgrass (F=34.73, P<0.001). The same tendency was observed for both grass species with regard to the number of days to ear initiation (large crabgrass: F=42.03, P<0.001) (Table 4.2). Maize grown in competition with naked crabgrass took 11 days longer to ear initiation on sandy soil. The number of maize ears was reduced by 50% where naked and large crabgrass was in competition with maize at the highest density (six plants per pot) on both soil types.

89

Table 4.2. The effect of naked and large crabgrass competition on days to 50% silking, ear initiation and number of ears of maize grown in two soil types.

Ratio (maize:grass)	Naked crabgrass			Large crabgrass		
	Clay	Sandy	Mean[a]	Clay	Sandy	Mean[a]
	50% Silking (days)					
1:0	58.75	70.50	64.62a	71.00	71.00	71.00a
1:2	63.57	72.75	68.16b	75.38	76.25	75.81b
1:3	66.00	74.75	70.36bc	78.88	80.63	79.75c
1:4	64.25	70.00	67.13b	81.50	85.00	83.25d
1:5	69.75	74.88	72.31cd	82.38	83.25	82.13d
1:6	71.75	78.13	74.94d	84.13	84.13	84.13d
Mean	65.69a	73.50b		78.88a	80.04b	
	Ear initiation (days)					
1:0	57.75	73.50	65.62a	71.88	73.63	72.75a
1:2	64.77	74.00	69.38ab	78.00	78.88	78.44b
1:3	66.00	76.00	71.00b	80.63	83.25	81.94c
1:4	65.00	74.25	69.62ab	82.38	84.13	83.25c
1:5	70.50	77.25	73.87bc	87.63	83.75	85.69d
1:6	72.50	84.25	78.37c	89.38	85.88	87.63d
Mean	66.09a	76.54b		81.65a	81.58a	
LSD(Ratio x Species)	n/s	1.35				
	Number of ears plant[-1]					
1:0	2.00	1.75	1.88a	1.88	1.75	1.81a
1:2	1.86	1.63	1.74ab	1.63	1.25	1.44b
1:3	1.75	1.00	1.38bcd	1.38	1.25	1.31bc
1:4	1.75	1.38	1.56abc	1.38	0.87	1.13cd
1:5	1.25	1.25	1.25cd	0.75	1.00	0.88de
1:6	1.13	0.88	1.00d	0.50	0.75	0.63e
Mean	1.63b	1.31a		1.25a	1.15a	

[a]Means within respective columns and rows followed by the same letter are not significantly different at P=0.05

90

4.4. Discussion

The complexity and various uncontrolled factors influencing weed-crop competition dynamics can impose analytical constraints on studying these interactions in field trials (Gibson, et al., 1999). Additionally, due to the fact that naked and large crabgrass is not readily distinguished from each other at the seedling and early vegetative stages, their competition effect on maize was studied separately in greenhouse trials to determine each species' competitiveness with maize. The advantages of trials in controlled environments can also assist to study other factors, such as soil type on the competition effect and growth of both weed and crop. We acknowledge that a single weed species rarely occurs solely in a production field, but grass control in a grass crop has specific challenges, where time of emergence and density of grass infestations play a major role in crop yield (Cathcart and Swanton, 2004; Fausey et al., 1997; Strahan et al., 2000; Young et al., 1984).

Apart from environmental conditions and factors, yield losses in maize are mainly caused by weed competition. The effect of grass infestations, especially from early on in the season, can result in severe yield losses since the weed and the crop has similar physiological pathways and nutrient source requirements (both being C_4 plants) (Fausey et al., 1997). As demonstrated by several weed-crop competition studies, competition for water, nutrients and light is the main limiting factor contributing to crop yield losses (Cerrudo et al., 2012; Fausey et al., 1997; Rajcan and Swanton, 2001). Similar to previous findings soil water content was found to be higher in naked crabgrass infested plots indicating rather a reduced ability of root systems to absorb water (Rajcan and Swanton, 2001). It is also acknowledged that root development and possibly root functioning were reduced due to space restriction of pots used. This SWC effect was, however, not apparent where large crabgrass was in competition with maize and SWC reduced as grass density increased, indicating effective uptake of water until silking of maize. In studies where soil water was not limited (i.e. production under irrigation), SWC did not differ between weedy and weed-free conditions as well (Tollenaar et al., 1997; Young et al., 1984). Soil water content is a parameter to define the availability of water for

91

plants in a specific soil type and optimum water content should be greater than 60% of field capacity to eliminate moisture stress on maize plants (Werner, 2002). The most important use of SWC is the quantification of the amount of water present in a well-defined volume of soil at a specific time. The measurement of SWC over time was therefore considered adequate to eliminate water as a competitor.

Although a decrease in N level ranged from 5 to 35% between soil types, both large and naked crabgrass densities showed competition for N from the seedling stage that could manifest in final maize yield loss. Several factors and physiological processes play a role in fertilizer availability, crop growth and the occurrence or control of weeds. The effect of soil fertility is, however, crop and weed species specific and in some cases weeds can benefit more from fertilization than crops (Harbur and Owen, 2004). Although several studies have been conducted to incorporate fertilization in an integrated weed control management program, results are contradictory and focussed mostly on nitrogen (Cathcart and Swanton, 2004; Evans et al., 2003b). Nitrogen is one of the most important nutrients in determining maize yield and fertilizer recommendations are therefore usually based on the soil available N and the yield potential of maize taking into account the hybrid and climatic conditions of a specific region (FSSA, 2007). Since N uptake occurs from the early seedling stages of maize up till three to five weeks after silking, competition with weeds have to be minimized to ensure optimum yields. Prolonged N uptake, especially during grain fill of maize, can increase leaf area and biomass, resulting in larger yields (Rajcan and Tollenaar, 1999). However, in the presence of weeds the availability of N will be altered along with dry mass accumulation (Cathcart and Swanton, 2004). Nitrogen deficiency symptoms are more likely to manifest faster under high weed pressure and some studies showed less developed root systems compared to weed-free maize (Tollenaar et al., 1994). Limited research has been done on other nutrients such as P and K.

Competition with either naked or large crabgrass resulted in reduced crop height, dry mass (shoots), number of ears and kernel weight of maize. Contradictory results exist with

92

regard to the effect of grass weed interference on maize height. Fausey et al., (1997) reported that giant foxtail (*Setaria faberi* (Herrm.)) competition with maize did not affect maize height while Cathcart and Swanton (2004) reported reduced height with increasing density of green foxtail (*S. viridis* (L.) Beauv.). The accumulation of above-ground dry matter of maize correlated positively with kernel number per plant, but can be influenced by hybrid choice and weather conditions (Cerrudo et al., 2012). A critical threshold level of dry matter accumulation has to be maintained around silking of maize to reduce the risk of barren ears. In this study a reduction in dry mass accumulation as observed in both maize competition trials with naked and large crabgrass can affect the ability of maize to maintain this threshold level significantly, resulting in reduced kernel set and weight. Cerrudo et al., (2012) also reported that stress (weed competition) early in the vegetative stages of maize, had a greater effect on dry matter accumulation and consequently reduced yield. The observed delay in the days to 50% silking and ear initiation suggested that grass weed competition by naked and large crabgrass could prolong the vegetative period of maize. This delay can lead to a reduction in the grain filling period with subsequent loss in kernel numbers and weight (Cerrudo et al., 2012; Tollenaar and Wu, 1999). When nutrient sources, light and soil water is not limited, the effect of weed interference may be more subtle, but both naked and large crabgrass showed severe competitiveness for the same sources required by maize. A lack of understanding of the competition effect between maize and weeds could be ascribed to the absence of studies taking root measurements into account (Rajcan and Swanton, 2001). For a holistic approach in understanding weed-crop competition, root development of both grasses and crop should be included in future research trials to elucidate the root: shoot ratio and the interaction thereof.

The hyperbolic model, using both naked crabgrass and large crabgrass density and total share in biomass (grass shoot mass and maize shoot and kernel mass), predicted maize yield loss successfully on both soil types. The high relation coefficients of determination ($R^2>0.96$ and $R^2>0.95$) are most likely due to the reduced effect of environmental factors and

single grass species competing with maize at the same plant size from commencement of the trials. The *I* and *A* values could only be influenced by soil type and density of grass species and not by environmental conditions (Aguyoh and Masiunas, 2003). Although the hyperbolic model fitted our data well the high asymptotes could be lower under field conditions. In the greenhouse trial, however, most maize plants in competition with six grasses per pot did not yield an ear or produced an ear with few kernels, emphasising the strong competitive ability of both naked and large crabgrass. The estimated yield loss of 95 to 100% yield loss can therefore be most likely when severe infestations of more than 50 grasses per m^2 prevail on especially sandy soils.

Several crop yield loss models describe losses in terms of weed densities, shoot dry mass, soil cover area of crop and weeds and leaf area index (Cousens, 1985; Kropff and Spitters, 1991; Lotz et al., 1996). Leaf area measurements are mostly used as the preferred variable to regress crop yield losses, but several studies used dry shoot mass successfully as well (Galon and Agostinetto, 2009). Furthermore, the maize canopy was above the canopy of the *Digitaria* grass weeds for the entire duration of the trial and the competition effect on leaf area would be more distinct in the grass weeds than in maize, concluding that competition for light may play a minor role in maize yield loss. The predictive capacity of these empirical models can, however, be compromised due to a lack of quantifying the effect of population dynamics, time of emergence (crop and weed) and the size of weeds especially (Gibson et al., 1999). However, Deen et al. (2003) evaluated four crop-weed competition models on a common data set and concluded that more complex models do not improve the fit of observed data sets. Although time of grass emergence can play a major role in crop yield losses, it was not a factor in this study. (See Chapter 5: Critical period of naked crabgrass control).

It is apparent from this study that biomass as well as grass density are reliable variables to predict and estimate maize yield loss when in competition with either naked or large crabgrass. According to Kropff and Spitters (1991), if the relative damage coefficient (q) is lower than one, the fitted curve will be concave, indicating that the crop is the stronger

94

competitor. Although the relative damage coefficients of both naked and large crabgrass were greater than one, the value for naked crabgrass competition on maize grown on clay soil was close to one, indicating an almost linear relationship. This means that the competition of naked crabgrass and maize on clay soil could be equal. Large crabgrass was the greater competitor compared to maize grown on both clay and sandy soil, while naked crabgrass was only a greater competitor when maize was grown on sandy soil. These models should, however, be verified in field trials on both crabgrass species.

In conclusion, soil type played a major role in the competitiveness of naked crabgrass, but did not influence the competitiveness of large crabgrass significantly. All maize growth parameters measured in this study were reduced when either naked or crabgrass densities were increased, confirming the competition effect of *Digitaria* grass weed species on maize. Both grass density and share in total dry mass of crop and weed can be used to predict yield losses in maize when naked or large crabgrass infestations prevail. It is estimated that a yield loss of greater than 10% can occur when approximately four naked or large crabgrass plants per m^2 are left to compete with maize. It is therefore critical to control both naked and large crabgrass infestations from emergence until the silking stage of maize to reduce the risk of high yield losses.

CHAPTER 5

Critical periods of weed control for naked crabgrass (*Digitaria nuda* Schumach.), a grass weed in maize in South Africa

Abstract

Difficulties to chemically control large crabgrass in maize in South Africa have recently been attributed to the occurrence of naked crabgrass, previously mistakenly regarded as large crabgrass, which, in contrast to the former, can be controlled relatively easily with acetanilide herbicides. Critical periods of weed control (CPWC) for naked crabgrass in maize was determined in field studies during the 2009/10 and 2010/11 growing seasons at two separate localities for an early and late planting date of maize. Weed-free and weed-crop interference treatments of increasing duration were maintained at various crop growth stages in the presence of naked crabgrass. Biomass of naked crabgrass was determined as dry weight per m^2 quadrant, which yielded 428 $g.m^{-2}$ at Potchefstroom and 594 $g.m^{-2}$ at Wesselsbron. An exponential regression model was used to determine the CPWC expressed as growing degree days after crop emergence, based on an estimated 10% relative yield loss in maize. The onset and ending, as well as, the duration of the CPWC differed between seasons and localities. At 10% relative yield loss, the onset of the CPWC ranged between the two (V2) and six (V6) leaf stages, and the ending between the twelve (V12) leaf stage and two weeks after tasseling (T + 2). The duration of the CPWC ranged between 22 and 80 days for the respective planting dates, years and localities. Yield losses ranged from 28 to 82% in the season-long weedy plots. The shifting of planting dates alone did not reduce yield losses since the effect of late infestations of naked crabgrass is significant. Naked crabgrass control from crop emergence is essential, followed by POST herbicide application during the critical period of weed control to lower the risk of maize yield losses.

5.1. Introduction

An increase in *Digitaria* species infestations reported by producers in the main maize producing region of South Africa recently lead to the identification of naked crabgrass [*D. nuda* (Schumach.)], a relative unknown *Digitaria* species in this region. Annual grass weeds that are recognised as difficult to control, in most maize producing areas of South Africa, include: large crabgrass (*D. sanguinalis* (L) Scop.), African goose grass (*Eleusine coracana* (L) Gaertn.), common buffalo grass (*Panicum maximum* Jacq.), Bushveld herringbone grass (*Urochloa mosambicensis* (Hack.) Dandy.) and herringbone grass (*Urochloa panicoides* Beauv.) (Botha, 2010; Bromilow, 2010). Although several *Digitaria* species occurs in most maize producing areas in South Africa, the weed status of the more uncommon *Digitaria* spp. such as, southern crabgrass (*Digitaria ciliaris* (Retz.) Koeler), velvet crabgrass (*Digitaria velutina* (Forssk.) Beauv.) and naked crabgrass is unknown. The growth cycle of these grasses coincides with maize production and their seeds germinate throughout the growing season of the crop (Saayman-Du Toit and Le Court De Billot, 1991). The importance and impact of large crabgrass has been studied world-wide in a variety of crops (Holm et al., 1977; Kim et al., 2002; Mitich, 1988). Naked crabgrass has been reported to be a grass weed in maize by several authors (Botha, 2010, Bromilow, 2010, Van Oudtshoorn, 2009) but the impact or competition on maize yields has not been reported, although it is recognised to be of importance in sugarcane in Brazil (Dias et al., 2005, Vieira et al., 2010) and is a serious grass weed in West Africa (Chikoye et al., 2000).

Typical grass control in maize production includes the application of PRE herbicides such as acetochlor, s-metolachlor and dimethenamid followed by cultivation four to six weeks after crop emergence. The planting of herbicide-tolerant maize cultivars (Roundup Ready® hybrids) validates the POST application of glyphosate to control grass weeds and is increasingly implemented by maize producers. A decrease in effective control with soil-applied, PRE acetanilide herbicides such as acetochlor and s-metolachlor has, however, been reported where severe infestations of naked crabgrass occurred. This is partly due to the

97

incorrect identification of species and prevailing misconceptions that acetanilide herbicides will control all *Digitaria* spp. equally well. Competition due to grass infestations in maize, predominantly large crabgrass and African goose grass resulted in significant yield losses if left uncontrolled. Jooste and Van Biljon (1980) reported that infestations of large crabgrass in maize can cause losses more severe than that caused by yellow nutsedge [*Cyperus esculentus* (L.)]*,* and can result in maize yield losses of up to 70%. Control of grass weed species is therefore essential during the first six weeks after crop emergence in order to prevent yield losses (Ghosheh et al., 1996; Hellwig et al., 2002)

The optimal timing of herbicide application is crucial to ensure effective control of grass species. The critical period of weed control (CPWC) is defined as the necessary duration of weed control to prevent yield reduction due to weed interference (Hall et al., 1992; Norsworthy and Oliveira, 2004; Page et al., 2009). Critical period of weed control is an estimation of the period during which crop growth and yields are negatively influenced by weed interference, to predict onset, critical- and end-point of CPWC (Singh et al., 1996). Two components are necessary to determine CPWC. These include the maximum period of time a crop can be exposed to early season weed competition before a yield loss threshold is reached, and the minimum duration of a weed-free period required after planting to prevent yield loss above an arbitrarily chosen threshold (Singh et al., 1996). Effective weed control during this period of crop development prevents serious yield losses and is the optimal time for herbicide applications (Evans et al., 2003a; Norsworthy and Oliveira, 2004; Williams, 2006).

Several studies on various weed species have been conducted to determine the CPWC for maize, but results vary and are often contradictory (Evans et al., 2003a; Gantoli et al., 2013; Ghosheh et al., 1996; Halford et al., 2001; Hall et al., 1992; Isik et al., 2006; Knezevic et al., 2002; Norsworthy and Oliveira, 2004; Page et al., 2009; Williams, 2006). The duration and especially the final stages of the CPWC in maize are greatly influenced by weed densities and spectrum, as well as variation in environmental factors (Evans et al., 2003b; Halford et al., 2001; Norsworthy and Oliveira, 2004). The beginning of CPWC in a no-till field

experiment was found to show less variability than CPWC in conventionally tilled soil (Halford et al., 2001; Hall et al., 1992). Evans et al. (2003a) concluded that the CPWC for maize started between crop emergence and the seven (V7) leaf stage and ended with anthesis. Isik et al. (2006) determined CPWC for maize in Turkey at 2.5, 5 and 10% yield loss thresholds and estimated the duration of the period to be five weeks at a 5% yield loss level. They found that the CPWC started at the first (V1) leaf stage and ended at the eight (V8) leaf stage, and that the CPWC increased to nine weeks when only a 2.5% yield loss level was predicted. When a yield loss of only 10% was predicted, the CPWC was only two weeks long. Williams (2006) reported that there was a significant interaction between planting date and CPWC of maize and that this could be used to optimize weed control programs. The duration of the CPWC increased for maize planted early and fields should be kept weed-free until the eight (V8) leaf stage, whereas the weed-free period was only up to third (V3) leaf stage for maize planted later. This significant effect was due to lower weed densities later in the season, influencing maize yield less than 5%. Norsworthy and Oliveira (2004) reported great variation in the duration of the CPWC for maize between localities. The beginning of the CPWC for one locality started from the first (V1) leaf stage (5 to 9 days after emergence) and ended between eight (V8) to ten (V10) leaf stages, while a CPWC of only four days (ending at V5 and V6) was recorded at another locality.

Most of the afore-mentioned critical periods were determined in cases where broadleaf weeds dominated the weed spectrum. Fewer studies have been done on the interference of grass species on maize yield (Anderson, 2000; Ghosheh et al., 1996). Weed interference by barnyard grass (*Echinochloa crus-galli* L. Beauv.), had a greater effect on maize planted early in the season when weed densities were highest compared to maize planted later in the season (Williams, 2006). Mickelson and Harvey (1999) determined that the density and time of emergence of woolly cupgrass (*Eriochloa villosa* (Thumb.) Kunth) had a significant effect on grass biomass and seed production. When the emergence of woolly cupgrass in maize was delayed, vegetative biomass and seed production of the weed grass declined rapidly,

99

indicating that late emerging grass may not be important for crop competition. Although grass species can germinate throughout a crop growth season, the incidence, densities and interference of grass weeds also varies greatly over different localities and seasons (Hartzler et al., 1999). Since naked crabgrass is a relatively unknown grass weed in maize production in South Africa the effect of early and late interference on crop yield is not known. This study was conducted to determine the CPWC and the effect on maize yields in those areas of South Africa where severe naked crabgrass infestations are experienced.

5.2. Materials and methods

Three field trials in which different CPWC were evaluated for naked crabgrass were conducted at two sites in the main maize producing regions of South Africa. A typical growing season for maize production in South Africa commences in November / December with planting in one year and concluded in May / June the following year with harvesting when maize is physiologically mature.

5.2.1. Experimental site 1

One field trial, consisting of an early and a late planting date, were established at the Agricultural Research Council's Institute for Grain Crops experimental farm situated in the North-West Province at Potchefstroom (S26°43'41.9", E27°04'47.8") during 2009/10 and 2010/11 growing seasons. Soil type was classified as a sandy clay-loam soil with a pH of 6.58, 36% clay, 59% sand and 5% silt (Appendix A: Table A.2). Naked crabgrass seed used to infest the CPWC trial was hand harvested during May 2008, threshed from mature Digitate-panicles, and left to dry before it was placed in polyethylene containers and stored for one year at 15 °C. Prior to establishing homogenous infestation levels of naked crabgrass, experimental fields were conventionally tilled early in spring (September 2009) with a mouldboard plough to a depth of 25 cm followed by disc cultivation to prepare a smooth seedbed in accordance with maize production practices used in the Northwest Province. Prior

100

to sowing grass or maize seed, atrazine / terbuthylazine, (Gesaprim® Super 291 / 291 ai g.l^{-1}, Syngenta South Africa (Pty Limited), Thornhill Office Park, 94 Bekker Street, Midrand, South Africa) was applied to soil PRE at a rate of 4 l.ha^{-1} for the control of broadleaf weeds. Naked crabgrass seed was hand sown on the soil surface, followed by 20 mm overhead irrigation one week prior to planting maize. A glyphosate-tolerant maize hybrid DKC78-35R was planted at an early (25 November 2009) and late (17 December 2009) planting date. This trial was repeated with the same maize hybrid in the same field during the following season with the early planting on 2 December 2010 and the late planting on 22 December 2010. During both seasons maize was planted with a Monosem air-pressured, 4-row planter calibrated to plant a density of 20 000 plants per hectare. Row spacing was 0.9 m and seeding depth was 6 cm, standard to local maize production practices.

The experimental design was a split-plot with planting date as main factor and treatments (12 weed interference periods) as subplots. Two control treatments were included, a season-long weed-free and a season-long weedy. The duration of weed interference and weed-free treatments were based on specific maize growth stages. Crop growth stages for maize were determined according to the system of Ritchie et al. (2003), where fully unfolded leaves were counted on maize plants when a visible collar was present in the season-long weed-free plots (e.g. V1 growth stage is where the first leave has fully unfolded). For weed interference period treatments, naked crabgrass were allowed to grow from crop planting up to the appropriate crop growth stage of V4, V6, V8, V10 and Tassel. The weed-free treatments consisted of weed-free periods up to V4, V6, V8, V10 and Tassel maize growth stages. Weeds were eliminated from the different interference treatments by spraying a 2% glyphosate dosage rate (Roundup Ready® Plus 540 g ae.l^{-1}, Monsanto South Africa, Monsanto House, Fourways Office Park, Fourways, South Africa) with an IRREMEC knapsack sprayer (25L) delivering 200 l.ha^{-1}. In order to protect maize plants from any adverse effects of glyphosate, directed spray applications were done using special spray covers over nozzles after the eight (V8) leaf stage. In the weed-free period treatments, naked crabgrass were

removed weekly by hand or by means of glyphosate until the appropriate duration of weed control was reached for the respective crop growth stages. Individual plot dimensions were six rows (5.4 m) by 5.5 m in length. Plots were randomized completely with three replications for each treatment at both early and late planting dates.

For the six weed interference treatments, naked crabgrass plants were sampled in 1 m^2 surface areas within the central four rows of each respective treatment plot, prior to glyphosate application. Biomass of grasses was determined after drying above-ground leaves and stems in an oven at 60 °C for 24 h. The only other grass species present at the trial sites were Bushveld herringbone grass and African goose grass, which could be clearly distinguished from *Digitaria* spp., and thus were hand-hoed to ensure homogenous infestation of naked crabgrass.

Crop and grass emergence in most treatments occurred simultaneously or within one week apart. Plant stand of maize was determined seven days after planting for each planting date during both seasons and expressed as percentage emergence. Emergence in all trials was commercially acceptable (>95%). Maize plants were harvested at physiological maturity and kernel moisture content was adjusted to 12.5%. The number of maize plants in the central four rows of each plot were counted (average of 75 plants per plot) and hand-harvested. Ears were de-husked and shredded after which total kernel mass and 1000 seed weight was determined. Yield (t.ha^{-1}) from the season-long weed-free plots was used to determine relative yield (%) and was regressed against growing degree days (GDD). The GDD was calculated using a simple model of the average daily maximum (Tmax) and minimum (Tmin) air temperatures minus the base temperature of maize (Tb = 10 °C) between November and May for each growing season (Williams, 2006). Planting date was used as the reference point for accumulation of GDD and the beginning and end of the CPWC for each locality were expressed in GDD and corresponding crop growth stage (CGS) (Evans et al., 2003a).

5.2.2. Experimental site 2

Another field trial consisting of an early and late planting date was established during 2010/11 growing season on a farm, near Wesselsbron (S27°42'47.9", E26°26'28.1") in the Free State Province. This site was characterized by severe natural infestation of naked crabgrass and no extra naked crabgrass seed were sown in at this locality. The soil type was classified as a sandy soil with 10% clay, 84% sand and 6% silt, with a pH of 5.62 (Appendix A: Table A.2). Conventional tillage practices for this maize production region were followed, i.e. rip cultivation (45 cm deep) during mid-October 2010.

The experimental design at this site was identical to that described above. However, at this site, each plot consisted of six maize rows, planted at wider inter-row widths of 1.5 m, 5.5 m in length. The wider inter-row width is standard practice to conserve soil moisture and may be unusually wide for producers in maize producing regions in the USA and Europe, but due to the low annual rainfall of between 450 to 500 mm, wider inter-row spacing is warranted for some maize producing areas in South Africa. Early planting of the maize hybrid DKC78-45BR (Monsanto South Africa) was done on 18 November 2010 and the late planting on 7 December 2010. Maize and naked crabgrass emergence was recorded seven days after seedling emergence in both early and late planting dates. Data collected were the same as for the Potchesftroom trial described above. Maize yield was determined by harvesting the middle four rows of each plot and the average number of plants harvested per plot was 58.

5.2.3. Statistical analysis

The data were analysed separately for each season and locality. The actual and relative yield data for early and late planting dates were subjected to an analysis of variance with planting date as main plot factor and weed interference or weed-free treatments as sub-plot factor. The residuals were tested for deviation from normality and no evidence against normality was found, therefore data were considered as reliable. The means of significant source effects

103

were compared using Fisher's Protected LSD at the 5% significance level. Relative yield data were analysed with a nonlinear (exponential) regression model to determine the effect of weed interference and weed-free periods to estimate the CPWC, the beginning (critical period of weed removal = CPWR) and end (critical weed free period = CWFP) of the period using the equation,

$$Y = A + BR^x \qquad [5.1]$$

where Y = relative yield (%), A + B = initial relative yield in weedy or weed-free plots, R = rate of yield loss, and x = duration of interference measured in GDD. This model represents a curve rising or falling from an asymptote (A) on the left of the graph if R > 1, and if 0 < R < 1 the curve rises or falls to an asymptote (A) on the right of the graph. The parameters of the regression model are listed in Table 5.3. The arbitrarily threshold levels of 5 and 10% yield loss was used to determine the CPWC (Knezevic et al., 2002). All data were analysed using Genstat for Windows 13[th]edn. Version 14 (Payne, 2011).

5.3. Results and Discussion

5.3.1 Yield responses

Cumulative rainfall at Potchefstroom was similar for early and late planting dates during 2009, (541 and 503 mm, respectively), while the late planting date during 2010 received 21% less rainfall (400 mm), compared to the early planting date (509 mm) (Figure 5.1). Although total rainfall between seasons at Potchefstroom differed, the distribution of rain affected maize yields more in the weed-free maize plots. Maize in weed-free plots yielded 31% less during 2010 compared to 2009 (5.59 and 8.16 t.ha^{-1}, respectively) (Table 5.1). At Wesselsbron cumulative rainfall was similar between early and late planting dates, but yield in weed-free plots differed between planting dates. Maize planted early yielded 22% more compared to maize planted later (5.19 and 4.07 t.ha^{-1}, respectively) (Table 5.2). Yield loss of maize

104

increased with the increased duration of grass interference and ranged between 28 and 55% for Potchefstroom and 37 and 82% for Wesselsbron in the season-long weedy plots (Tables 5.1 and 5.2). Yield was only influenced by the planting date at Potchefstroom during 2009 where the late planting yielded on average 1 t.ha^{-1} more. At Wesselsbron the early planting date yielded 1.5 t.ha^{-1} more than the late planting date during 2010.
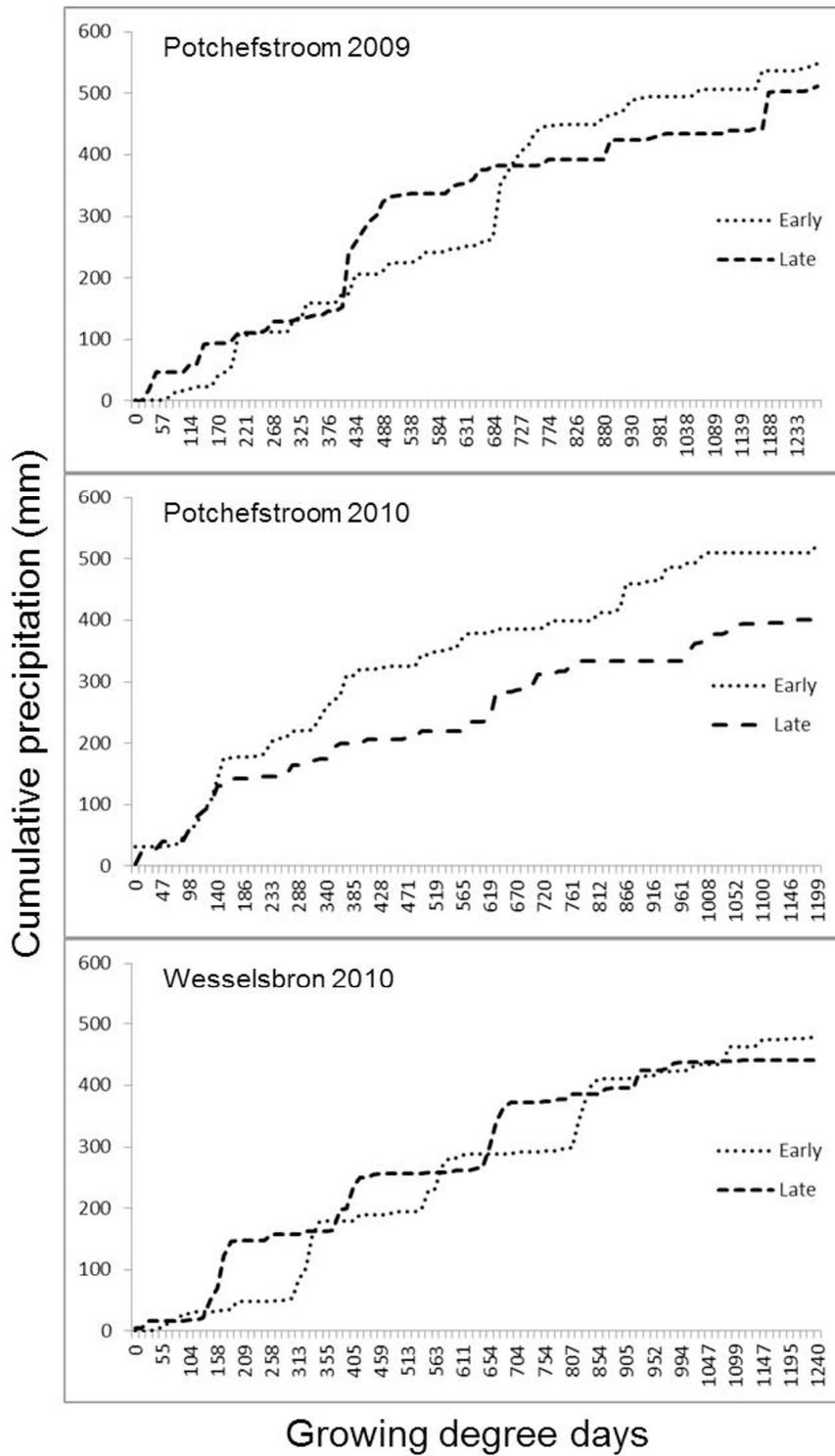
Figure 5.1. Cumulative rainfall plotted against growing degree days after planting of maize for two planting dates (early and late) at Potchefstroom and Wesselsbron during 2009/10 and 2010/11 growing seasons.

Table 5.1. The effect of weed interference periods on maize yield (t.ha^{-1}) at Potchefstroom where maize was planted early and late during two seasons.

	Weed interference	2009/10			2010/11		
		Early	Late	Mean	Early	Late	Mean
		t ha^{-1}					
	Weed-free Control	7.76	8.56	8.16	5.93	5.25	5.59
	V4	6.69	8.48	7.59	5.30	4.83	5.07
Weed free	V6	4.72	6.32	5.52	5.13	4.41	4.77
up to	V8	5.20	7.16	6.18	4.37	4.23	4.30
	V10	3.52	6.91	5.22	4.29	3.91	4.10
	Tassel	3.86	5.54	4.70	4.07	4.19	4.13
	Weedy Control	3.53	4.94	4.23	3.82	3.76	3.79
	V4	5.50	5.34	5.42	3.95	4.09	4.02
Weedy	V6	6.58	5.13	5.85	4.06	4.74	4.40
from	V8	5.74	7.01	6.37	4.19	4.42	4.31
	V10	7.14	6.76	6.95	4.90	5.43	5.17
	Tassel	7.63	7.28	7.45	4.83	5.58	5.20
	Mean	5.66	6.62		4.57	4.57	
	LSD$_{(Planting date)}$	0.97			n/s		
	LSD$_{(Treatments)}$	1.31			n/s		
	LSD$_{(Planting date X Treatments)}$	1.90			n/s		

107

Table 5.2. The effect of weed interference periods on maize yield (t.ha^{-1}) at Wesselsbron where maize was planted early and late during one season.

		2010/11		
	Weed interference	Early	Late	Mean
		t ha^{-1}		
	Weed-free Control	5.19	4.07	4.63
	V4	3.85	2.65	3.25
Weed free	V6	4.40	2.98	3.69
up to	V8	3.72	1.95	2.84
	V10	4.05	1.97	3.01
	Tassel	3.48	1.12	2.30
	Weedy Control	3.28	0.72	2.00
	V4	4.62	3.12	3.87
	V6	4.76	3.76	4.26
Weedy from	V8	4.55	3.75	4.15
	V10	4.82	4.12	4.47
	Tassel	4.66	3.54	4.10
	Mean	4.28	2.81	
LSD(Planting date)		0.63		
LSD(Treatments)		1.26		
LSD(Planting date X Treatments)		n/s		

5.3.2. Weed growth and biomass

Naked crabgrass emergence and growth was slower at Potchefstroom during 2009 as indicated by the dry biomass of only 183 and 169 g.m^{-2} for the early and late planting dates respectively. During 2010 biomass of naked crabgrass was 21 and 60% higher for the early and late planting dates respectively (Figure 5.2) and can be ascribed to higher re-infestation

108

after seed shedding during May 2010. Naked crabgrass biomass was much higher at Wesselsbron compared to Potchefstroom and yielded 418 and 594 g.m^{-2} in the early and late planting dates and can ascribed to the natural infestation build-up over years. The highest biomass at Wesselsbron was recorded 78 days after crop emergence, which corresponded with tasseling of maize plants (Figure 5.2).
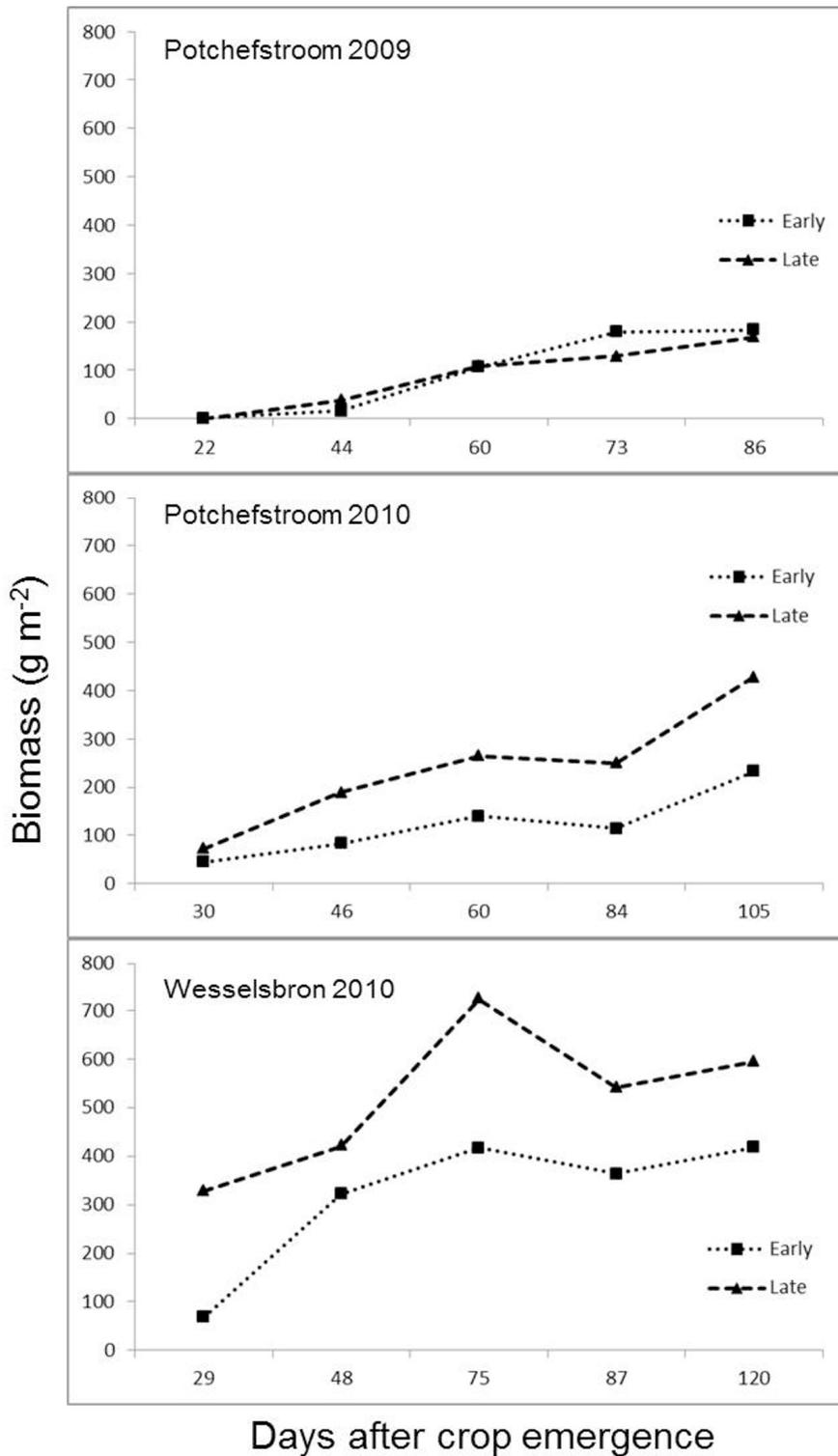
Figure 5.2. Naked crabgrass biomass for two planting dates (early and late) measured in weedy interference plots in 1m² quadrants at Potchefstroom and Wesselsbron during 2009/10 and 2010/11 growing seasons.

110

This could be explained by the morphological growth patterns of naked crabgrass tufts that formed a thick carpet of dense growth within weeks after crop emergence at Wesselsbron, unlike grass growth at Potchefstroom where dense mat-forming growth started later and was limited due to canopy formation of maize. The difference in incidence of naked crabgrass between the two localities can be attributed to various factors such as seed bank composition, climatic conditions, soil type and tillage practices (Knezevic et al., 2002). The wider inter-row spacing at Wesselsbron allowed grass to grow vigorously from early on in the season without competing for light since maize plants did not form a canopy between rows. Norsworthy and Oliviera (2004) found that the CPWC and maize competitiveness is not affected by row-widths, but that canopy formation is needed to reduce emergence and regrowth when weed species tend to exhibit continuous emergence patterns. If resources such as light, nutrients and soil moisture are not limited, naked crabgrass could emerge until late in the crop growth season, indicating that season-long weed control is needed. However, such long periods of effective weed control is in most cases not practical and very costly. Late emergence of certain grass species such as woolly cupgrass has little to no effect on maize yield (Mickelson and Harvey, 1999). Similarly Bosnic and Swanton (1997) established that barnyard grass infestations early in the season is more detrimental to maize yield but concluded that it is rather time of emergence than weed density that is more critical to maize yield. Grass emergence can also be greatly influenced by soil tillage and some grass species were found to be more prevalent under no-till conditions where increased densities of foxtails species and barnyard grass were observed and showed longer periods of emergence when compared to conventionally tilled soil (Buhler, 1992; Halford et al., 2001).

5.3.3. Critical periods of weed control

Because of significant main effects between seasons and planting dates observed for yield data, relative yield data were not pooled over seasons or planting dates. Both periods of

weedy and weed-free curves fitted to relative yield had high coefficients of determination (R^2) and was significant at the 5% level for both localities and all seasons (Table 5.1).

Table 5.3. Exponential equations for relative yield (Y) in the function of growing degree days (GDD) measured after crop emergence with interference of naked crabgrass in maize used to determine CPWC in Figures 5.3 and 5.4. The beginning and end of the period was determined using the equation Y = (A + B)R$^{(x)}$ (Eq. 5.1). Standard error of the means is indicated in brackets.

Locality (season)	Planting date	Parameter		Weedy	Weed-free
Potchefstroom (2009)	Early	A		25.4 (29.9)	112.0 (19.2)
		B		76.3 (27.8)	-65.5 (17.9)
		R		0.998 (0.001)	0.998 (0.001)
			R^2	0.92	0.93
	Late	A		178.0 (482.0)	35.4 (70.30)
		B		-78.0 (476.0)	22.2 (65.0)
		R		1.000 (0.001)	1.001 (0.001)
			R^2	0.79	0.83
Potchefstroom (2010)	Early	A		33.4 (41.0)	63.4 (6.57)
		B		67.1 (39.5)	1.5 (3.0)
		R		0.999 (0.0005)	1.002 (0.001)
			R^2	0.96	0.89
	Late	A		61.8 (18.6)	116.4 (17.3)
		B		38.6 (17.1)	-50.2 (15.8)
		R		0.999 (0.001)	0.999 (0.001)
			R^2	0.89	0.93
Wesselsbron (2010)	Early	A		62.6 (14.3)	92.8 (2.43)
		B		34.9 (13.8)	-29.6 (5.22)
		R		0.998 (0.001)	0.995 (0.001)
			R^2	0.77	0.89
	Late	A		-208.0 (548.0)	97.1 (4.52)
		B		307.0 (544)	-79.6 (7.94)
		R		0.999 (0.001)	0.996 (0.001)
			R^2	0.96	0.97

The exponential curve (asymptotic regression model), which overlapped in all cases, could be used to determine both the critical time of weed removal and critical weed-free period and CPWC for naked crabgrass control in maize. The acceptable level of yield loss is an arbitrarily decision that should be made considering the cost of weed control and possible incomes from crop harvests (Knezevic et al., 2002). Input costs for maize production and grain price in South Africa vary greatly between seasons and chemical weed control is estimated to comprise 11% of input costs (Grain SA, 2013). The relative yield loss regressed to GDD for a 10% threshold level where a definite CPWC could be determined for maize at both localities and at different planting dates (Figures 5.3 and 5.4). The corresponding crop growth stage has, however, been determined for both the 5 and 10% threshold levels and is presented in Table 5.4. The duration of the CPWC varied considerably between planting dates and seasons and no concomitant CPWC could be determined for either planting dates or localities. During 2009 the CPWC for the late planting date (73 days) was twice as long as observed for the early planting date (36 days) (Figure 5.3 A and B).

113
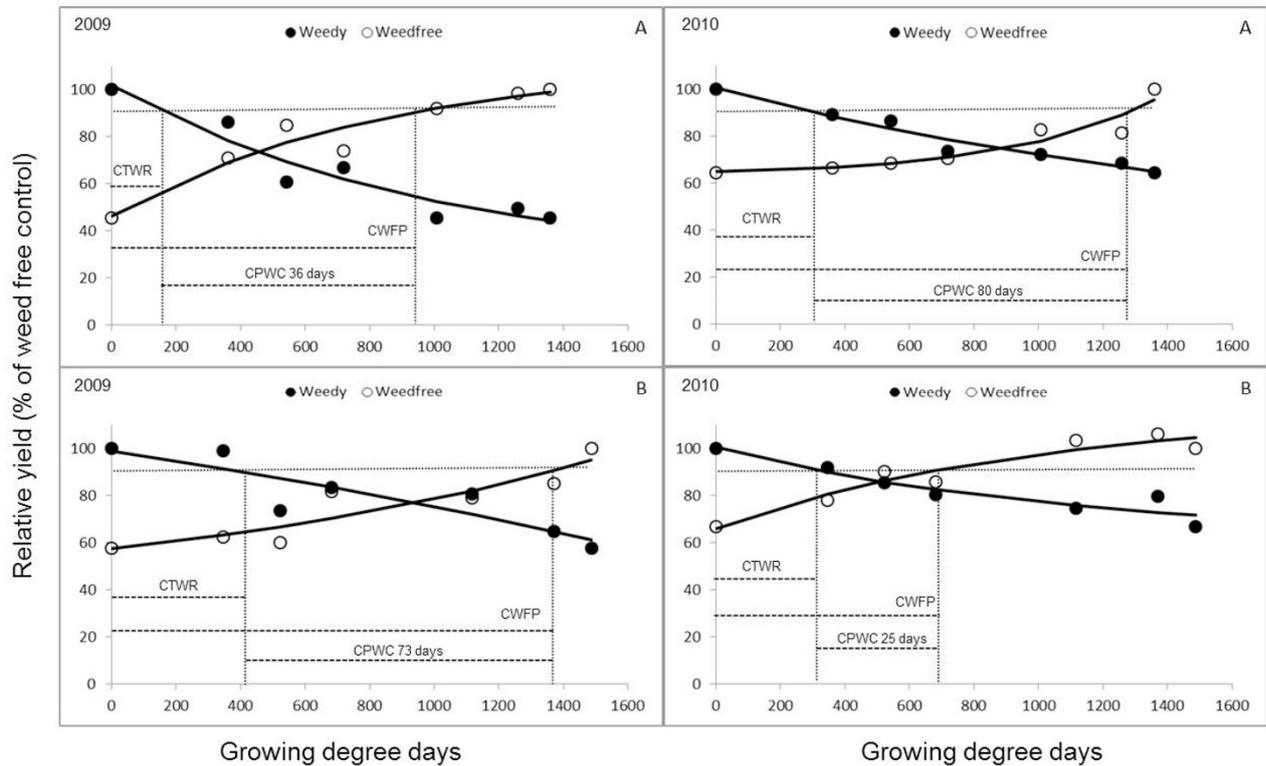
Figure 5.3. Critical periods of weed control (CPWC = vertical lines) of naked crabgrass in maize estimated for a yield loss of 10% during A) early and B) late planting at Potchefstroom for the 2009/10 and 2010/11growing seasons. CTWR = critical time of weed removal; CWFP = critical weed free period. Relative yield losses were calculated from samples of 78 plants per plot and were fitted to the following exponential response equation: $y=(A+B)R^{(x)}$. (Equation parameters Table 1)

This tendency was also observed between the early and late planting dates for Wesselsbron during 2010 (22 days compared to 42 days) (Figure 5.4 A and B). During 2010 the duration of the CPWC for the late planting date at Potchefstroom was, however, considerably shorter at 25 days compared to the early planting date where it was 80 days. At a 5% threshold level the duration of CPWC for naked crabgrass in maize increased for all trials (Table 5.4). Reported durations for most CPWC in maize is, however, relatively short when yield losses of greater than 5% were expected and is reported to range between 12 and 44 days (Isik et al., 2006; Norsworthy and Oliveira, 2004).

114
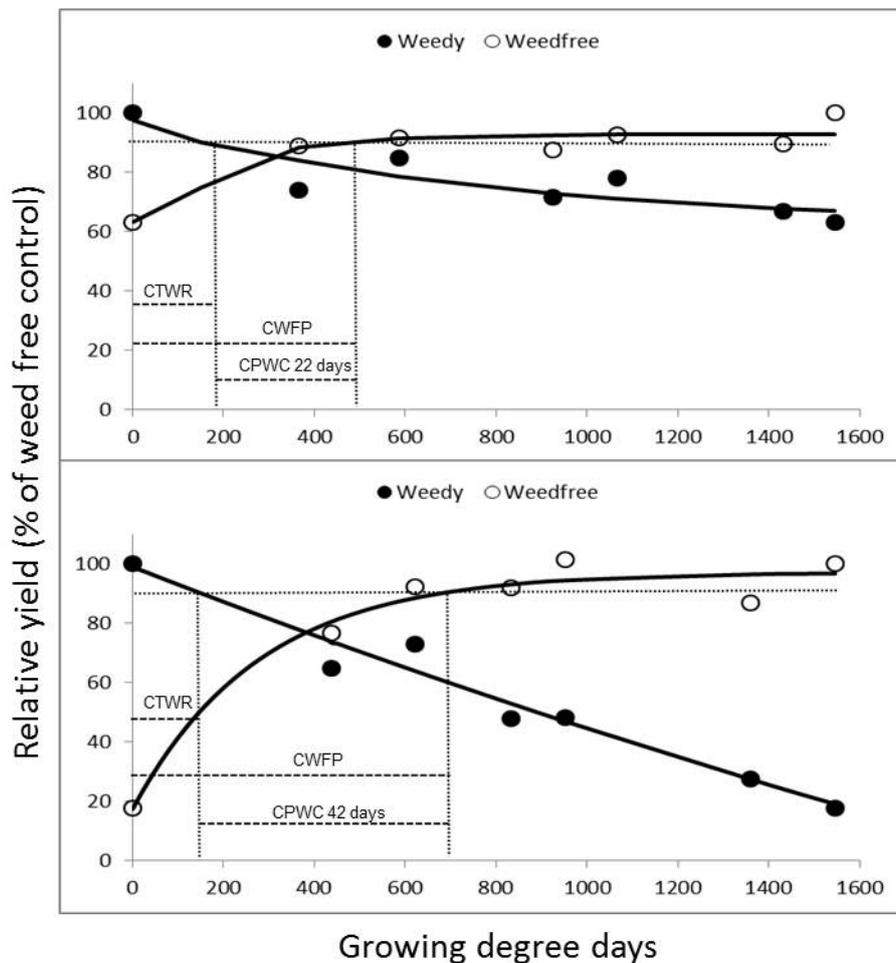
Figure 5.4. Critical periods of weed control (CPWC = vertical lines) of naked crabgrass in maize estimated for a yield loss of 10% during A) early and B) late planting at Wesselsbron for the 2010/11 growing season. CTWR = critical time of weed removal; CWFP = critical weed free period. Relative yield losses were calculated from samples of 58 plants per plot and were fitted to the following exponential response equation: $y=(A+B)R^{(x)}$. (Equation parameters Table 5.1)

The CPWC for Potchefstroom during 2009 commenced at the two (V2) and six leaf (V6) stages for the early and late planting dates respectively. During 2010 the beginning of the CPWC was more stable at both Potchefstroom and Wesselsbron and started at the four (V4) and the two (V2) leaf stages for the early and late planting dates (Figures 5.3 and 5.4). The end of the CPWC showed, however, more variation and ranged from the six leaf stage (V6) to two weeks after tasselling (T+2) of maize between the localities and years (Table 5.4).

115

Table 5.4.The critical period of weed control (CPWC) for maize at two planting dates and two localities during 2009/10 and 2010/11growing seasons expressed in crop growth stage (CGS) at a 5 and 10% yield loss level.

Locality	Planting date	CPWC	CGS 5	CGS 10
			%	
Potchefstroom 2009/10	Early	Beginning	V1	V2
		End	V14	V12
	Late	Beginning	V3	V6
		End	R1	T+2
Potchefstroom 2010/11	Early	Beginning	V2	V4
		End	T+4	T+2
	Late	Beginning	V2	V4
		End	V10	V8
Wesselsbron 2010/11	Early	Beginning	VE	V2
		End	-	V6
	Late	Beginning	VE	V2
		End	V12	V8

This is in contrast with the findings of Hall et al. (1992) which concluded that the beginning of the CPWC is often more variable compared to the ending. They found that the beginning of the CPWC varied between the three and fourteen leaf stages while the ending was usually at the fourteen leaf stage of maize. Early onset of the CPWC has been reported for maize in several studies indicating the need for weed control from crop emergence onwards (Evans et al., 2003a; Isik et al., 2006; Norsworthy and Oliveira, 2004). Norsworthy and Oliveira (2004) reported the onset of CPWC for maize to be as early as five days after crop emergence, despite different row-widths. In a study done by Williams (2006) the planting date of maize significantly influenced the start and ending of CPWC period and it was concluded that maize

116

planted early showed higher yield losses than maize planted later. This was evident due to higher weed infestation levels early in the season. All the above mentioned studies estimated the periods of critical weed control for a weed spectrum that was dominated by broadleaf weeds where numbers started to decline later in the season. Based on own observations naked crabgrass can, however, germinate and emerge throughout the growing season if favourable growing conditions prevail, emphasising the lengthy critical period of weed removal observed at both localities.

Based on the 5 and 10% estimated yield loss levels the CTWR (beginning) and CWFP (end) of the CPWC differed among seasons and localities. These periods were however found to be in the same range of critical periods recorded in other CPWC studies done for maize (Gantoli et al., 2013; Hall et al., 1992; Isik et al., 2006; Williams, 2006). Early control of naked crabgrass in the maize cycle is crucial when heavy infestation levels of grass species are anticipated and season-long control is the safest option, despite deviation in planting date. Whether this approach would be economical is, of course, another matter. Integrated weed management practices such as the application of pre- and POST herbicides, together with soil tillage to bury seed will likely be more effective than herbicides alone to reduce germination of viable naked crabgrass seed. Season-long germination was experienced at both localities and late infestations can still cause severe yield reductions, ranging from 28 to 82%. Maize producers should be made aware of the consequences of incorrect identification of *Digitaria* species, since it seems as if naked crabgrass grows more vigorously than large crabgrass and can cause severe yield losses depending on infestation levels. Although maize producers rely heavily on POST herbicide applications when minimum or no-tillage is practiced, high naked crabgrass infestations can conceivably be significantly reduced with deep soil tillage to decrease viable seed in the seedbank. The timing of POST herbicides is furthermore crucial for significant weed control (Knezevic et al., 2009). Both maize and grass weeds are C_4 plants, which means that having the same photosynthetic pathways will enhance their competitive interactions. The period of maize development during tasseling and silking is critical for ear

and grain development, and weed competition during these periods should therefore, be kept to a minimum. The CPWC values determined in this study showed that season-long weed control is essential to prevent yield loss, which makes POST herbicides applied during the critical period of weed control a logical choice for prolonged grass control.

CHAPTER 6

Comparative efficacy of herbicides registered on maize to control large crabgrass

(*Digitaria sanguinalis* (L.) Scop.) and naked crabgrass (*D. nuda* Schumach.)

Abstract

Acetochlor and s-metolachlor (chloroacetamide group) are graminicides predominantly used to control grass weeds in maize and are applied PRE. A greenhouse study was conducted using two soil types to determine the efficacy of these herbicides for control of both large and naked crabgrass which closely resemble each other. Large crabgrass was completely controlled for six weeks while naked crabgrass was only controlled for three weeks after herbicide application on a clay soil. Control of both herbicides was less effective when applied to a sandy soil. Naked crabgrass seedlings started to emerge two weeks after herbicide application and increased to more than 50% when compared to control treatments. Large crabgrass emerged between three and five weeks after application. In a field trial nine herbicide programs, registered for large crabgrass control in maize were evaluated for control of naked crabgrass. A single application of PRE herbicides (chloroacetamide group) gave poor control of only 60% for three weeks after application. Re-infestation of naked crabgrass was >50% within six weeks after application. Naked crabgrass control in herbicide programs consisting of only one POST application of either glyphosate or paraquat was less than 44% due to re-infestation (60%) two weeks after application. Naked crabgrass was most effectively controlled (85 – 100%) in herbicide programmes consisting of PRE applications from herbicides in the chloroacetamide group followed by POST applications of herbicides containing triketones. The residual activity on naked crabgrass for acetochlor and s-metolachlor was 16 days, compared to 51 days for herbicides containing triketones. Naked crabgrass failed to produce inflorescence within 10 weeks after seeding in the herbicide programmes receiving pre- and POST applications preventing concomitant seed shedding.

119

Late infestation levels of naked crabgrass can be significant and in areas where this *Digitaria* spp. has been predominantly identified, effective control will only be achieved with PRE herbicides followed by POST herbicide application three to four weeks after planting to prevent significant yield losses.

6.1. Introduction

The profitability of maize (*Zea mays* L.) production in South Africa is under continuous pressure due to increasing input costs and risks involved to produce sustainable yields. Weed control contributes up to 11% of the total input costs of maize production and effective control is crucial for producers to ensure a stable economic threshold level. Planting of maize in South Africa is generally followed by pre-emergence (PRE) application of herbicides from the acetanilide family in combination with wide spectrum broadleaf herbicides containing active ingredients from the triazine group. Most applied PRE herbicides in South Africa include acetochlor, s-metolachlor, s-dimethenamid and alachlor, corresponding with soil applied herbicide usage in the USA (Allemann and Mphundi, 2010; Myers et al., 2005). PRE applications of herbicides are critical for early season control due to the germination of high numbers of weed seeds present in soil that will exceed crop growth early in the season, increasing the risk of yield loss. One of the prerequisites of soil applied grass herbicides is follow-up precipitation to activate herbicide in the soil, enhancing its efficacy. Lack of precipitation results in reduced efficacy and late emerging weeds, of which especially grasses can cause significant reductions in crop yields (Tapia et al., 1997).

Post-emergence (POST) herbicides registered for grass control in maize can be an option and applications thereof has increased with the trend to plant crops with reduced or no tillage, but the timing of the application is crucial for effective control (Culpepper et al., 1998, 2001; Myers et al., 2005). Heavy rainfall either before or after herbicide application can complicate control management since wet fields will prohibit application and heavy rainfall

120

directly after application can reduce efficacy of POST herbicides significantly. Herbicide-resistant crops such as Roundup Ready® maize can simplify weed control in herbicide resistant maize to a great extent, but timing of application and the growth stage of weeds play a major role in the effectiveness of glyphosate as well (Ferrel and Witt, 2002; Myers et al., 2005). Furthermore, effective control of grass weeds depends on the height of grass at the time of application. Grass species such as giant foxtail (*Setaria faberi* Herrm.), barnyard grass [*Echinochloa crus-galli* (L.) Beauv.] and large crabgrass have to be controlled before they reached 15 cm in height (Tapia et al., 1997).

It is essential to identify grass species correctly within and between species (Chapter 2) for it is possible for one active ingredient to effectively control certain grass species such as *Panicum* species but not *Digitaria* spp. (Norsworthy and Meehan 2005). Broadleaf signal grass [*Brachiaria platyphylla* (Griseb.) Nash] was found to be more tolerant to alachlor than fall Panicum [*Panicum dichotomiflorum* (L.) Michx.] and large crabgrass [*Digitaria sanguinalis* (L.) Scop.] (Johnson and Coble, 1986). Herbicide selectivity has also been recorded within *Digitaria* spp., making the choice of herbicide that more complex (Dias et al., 2005). Due to the abundance of seed production of most grass species, early season control is essential to prohibit grass weeds to shed seed and replenish the seedbank.

Extensive use of only certain herbicides or herbicides within the same group can cause a shift in weed spp. composition as well as an increase in the frequency of herbicide resistant weed populations (Norsworthy, 2008). The misuse of one herbicide as the only means to control weeds can lead to resistant weed populations over time. Within 10 years of the introduction of Roundup Ready® cultivars in 1996, 12 weed species had become resistant to glyphosate, and there are currently more than 24 species exhibiting this resistance (http://www.HRACglobal.com). Accessions of large crabgrass resistant to ACCase inhibitors have been observed by Wiederholdt and Stoltenberg (1995; 1996). Extensive use of atrazine resulted in the predominance of fall *Panicum* (Coffman and Frank, 1992) while goose grass [*Eleusine coracana* (L.) Gaertn.] increased with sole application of ALS inhibitors.

121

Although problematic, *Digitaria* species such as large crabgrass and southern crabgrass [*D. ciliaris* (Retz.) Koeler] are controlled effectively with herbicides containing acetochlor, s-metolachlor or glyphosate (Doub et al., 1988; Ferrel and Witt, 2002). The control of less known *Digitaria* spp. is not well documented. Most product labels registered in South Africa for grass control in maize include large crabgrass on the list of grasses. Callisto (Syngenta, AG South Africa, a.i. mesotrione) is the only product that mentions naked crabgrass as "difficult to control" on its label. The objective of this study was to determine 1) the efficacy of acetochlor and s-metolachlor on both large and naked crabgrass on two soil types, and 2) to compare efficacy between herbicide programs used in maize production for the control of naked crabgrass since increasing reports of ineffective control of *Digitaria* species have been received.

6.2. Materials and methods

6.2.1. Experiment 1: Greenhouse trial

The efficacy of two PRE herbicides containing acetochlor (Guardian S® EC, 840g.l⁻¹) and s-metolachlor (Dual® S Gold EC,915 g.l⁻¹) were determined in a greenhouse trial using two soil types to compare control of large crabgrass and naked crabgrass. Seed of large crabgrass was collected at Cedara, (S29°32'15.28", E30°16'09.11") KwaZulu-Natal and seed of naked crabgrass was collected at Potchefstroom, (S26°43'41.9", E27°04'47.8"), North-West Province. Seed was stored in paper bags at 15°C until used. A sandy loam soil (16% clay, 5% silt, 79% sand) and sandy clay loam soil (36% clay, 5% silt, 59% sand) were separately sterilized with methyl bromide (3.5 kg gas for 35 m²), sieved and placed into rectangular plastic containers measuring 320 X 445 X 90 mm. Large crabgrass and naked crabgrass seeds were sown separately into containers to ensure no contamination between species on both soil types. Containers were placed on different tables in the greenhouse to separate the two species. Soil was hand cultivated after seeding with a small garden tool to incorporate

122

grass seeds within the top 1 cm of soil and firmly rolled with small paint rollers to enhance

seed-soil contact necessary for germination. (See Table 6.1. for dosage rates)

Table 6.1. Herbicide spray programs applied to a clay loam soil (36% clay) to determine the efficacy of naked crabgrass control in two field trials.

Product name	Active ingredient (formulation g.l^{-1})	Dosage rate (l.ha^{-1})
PRE spray program		
Acetochlor	acetochlor (700)	2.5
Dual® Gold	s-metolachlor (915)	1.0
Guardian® S	acetochlor (840)	1.7
POST spray program		
Halex® GT	glyphosate (250a.e[a].)/ mesotrione (25)/ s-metolachlor (250)	5.0
Gramoxone	paraquat (200)	1.5
Roundup® Ready Plus	glyphosate (450a.e.)	4.0

PRE followed by POST spray program					
PRE			POST		
Product name	Active ingredient (formulation g.l^{-1})	Dosage rate (l.ha^{-1})	Product name	Active ingredient (formulation g.l^{-1})	Dosage rate (l.ha^{-1})
Dual® Gold + Callisto	s-metolachlor (915) + mesotrione (480)	0.71 0.21	Primagram® Gold + Callisto	atrazine (370)/ s-metolachlor (290) + mesotrione	1.8 0.26
Guardian®S	acetochlor (840)	1.7	Laudis®+ Atrazine + Ballista	tembotrione (420) + atrazine (500) + Ballista[b]	0.12 1.0 0.5
Frontier® Optima	s-dimethenamid (720)	1.0	Stellar™ L Dash™HC	dicamba(160) / topramezone (50) + Dash[b]	0.70 1.0

[a]acid equivalent, [b]Adjuvants

Pre-emergence (PRE) herbicides were applied at registered dosage rates according

to each active ingredient and soil clay percentage: acetochlor at 1.0 l.ha^{-1} (sandy soil) and 1.7

l.ha^{-1} (clay soil); s-metolachlor at 0.8 l.ha^{-1} (sandy soil) and 1.0 l.ha^{-1} (clay soil). Treatments

123

included a weedy control where no herbicides were applied. Trial layout was a complete randomized block design, replicated eight times for each soil type. Herbicides were applied one day after planting of seed using a CO_2 powered conveyer-band sprayer fitted with one TeeJet 8004E band nozzle, delivering a volume equivalent to 250 l.ha^{-1} at 200kPa. Each container was placed separately on the conveyer band to ensure effective application while control treatments received no herbicide applications. After herbicide application each container was watered with 250 ml to activate PRE herbicides and thereafter watered daily as required.

Emergence (number of grasses) in treatments was recorded when two leaves of grasses could be visually observed and subsequent emergence was recorded weekly for up to eight weeks after application (WAA). Efficacy of herbicides treatments (% control) was expressed as a function of the mean number of grasses emerged in control treatments over time (WAA).

6.2.2. Experiment 2: Field trial 1

Seed of naked crabgrass was sown during November 2011 at the experimental farm of the Agricultural Research Council's Grain Crops Institute at Potchefstroom to ensure sufficient infestation levels. Nine herbicide programs, commonly used to control grass infestations in maize production in South Africa, were compared for their efficacy to control naked crabgrass. No crop was planted and the soil was a sandy clay loam soil with pH 6.58 and 36% clay, 5% silt and 59% sand content. Three programs included one PRE application, three programs included one POST application and three programs included PRE followed by POST applications. The respective products with their formulations, active ingredients and dosage rates are presented in Table 6.1. Herbicide dosage rates were applied according to the registered label rate for each active ingredient. A weedy control treatment where no herbicides were applied and a clean control treatment where grass weeds were hand hoed was also

124

included. Herbicides were applied using an experimental tractor sprayer with six separate 20 litre tanks delivering 220 l.ha^{-1}.

The trial layout was a complete randomized block design with four replicates with individual plot sizes of 5 m X 5 m. Broadleaf weeds and other grass weeds, mainly herringbone grass (*Urochloa panicoides* Beauv.*)*, were hand hoed to ensure homogenous naked crabgrass growth. All PRE herbicides were applied on 29 November 2011 and plots were irrigated (20 mm) the following day to ensure activation of herbicides. The once-off POST herbicide applications were done 22 days later when naked crabgrass seedlings were between the four and six leaf stages and still emerging but not taller than 10 cm. No excessive rainfall was received directly (for eight hours) after POST application, ensuring effective application. In the programs receiving PRE followed by POST applications, POST herbicides were applied four weeks after initial PRE herbicides when successive grass seedlings were observed to be between the two and four leaf stages.

Grass control was evaluated three and eight weeks after application (WAA) in the programme that received only once-off PRE herbicides and two and eight weeks after the POST applications in the programs receiving only once-off POST or a follow up POST. The number of naked crabgrass seedlings emerged was counted in each treatment block at the above mentioned times (2, 3 and 8 WAA) and percentage control for each treatment was expressed as a function of the mean number of naked crabgrass seedlings recorded in control treatments. The percentage grass cover (mat-forming of tufts) was visually rated on a 0 to 100% scale where 0% indicated no grass coverage and 100% indicated complete coverage of a treatment block (25 m^2). The increase in percentage grass cover was recorded at fortnightly intervals until 12 weeks after grass emergence. Where possible subsequent seedling emergence was counted to determine residual activity of herbicides applied. Plant height of 10 naked crabgrass tufts was measured in each plot when inflorescences were maturing, eight weeks after grass emergence. Above-ground biomass of naked crabgrass was sampled in two 1 m^2 quadrants per plot. Where naked crabgrass formed a carpet / mat, quadrants were

placed on top of the grass mat and spaded off at each side to keep variation to a minimum. The above-ground plant material was dried at 60 °C for 48 h to determine dry mass.

6.2.3. Experiment 3: Field trial 2

A second field trial was conducted during December 2012 at the same trial site used in experiment 2. The entire field trial was repeated, but this time the maize cultivar PAN6Q-708BR (Pannar, South Africa) was planted on 5 December 2012. Prior to planting the trial site was tilled with a mouldboard plough to a depth of 15 cm followed by a shallow disc-tillage for seedbed preparation. Each plot consisted of four maize rows with inter-row spacing of 0.9 cm, planted with a Monosem air-pressurized planter at a plant density of 20 000 plants per hectare (standard for Northwest production area). PRE applications were done immediately after planting and all the POST applications were done four weeks after planting of maize when naked crabgrass was between the four and six leaf stages. The spray programs were exactly applied as described for experiment 2 (Table 6.1). Irrigation was applied within four days after PRE herbicide applications and as needed during the growing season.

The percentage control and coverage of naked crabgrass was determined for each treatment plot (25m^2) four and eight weeks after herbicide applications and percentage control for each treatment was expressed as a function of the mean number of naked crabgrass seedlings recorded in control treatments. Broad leaf weeds and other grass weed species were hand hoed from plots to ensure homogenous competition of naked crabgrass. The middle two rows of each plot were hand harvested on 20 May 2013 when maize was physiological mature. Ears were de-husked and weighed to determine total ear weight. After threshing total kernel weight was determined and moisture was adjusted to 12.5% to determine yield in metric tonnes per hectare.

126

6.2.4. Statistical analysis

Emergence and efficacy of control (% control) of naked crabgrass and large crabgrass in the greenhouse trial was analysed separately using an analysis of variance with herbicide treatments, soil type and time of emergence (weeks after application) as factors. Data from field trials i.e., grass height, dry mass (grass) and yield data (maize) were subjected to a one-way analysis of variance with herbicide treatments as a factor. Percentage grass cover and control in both field trials were analysed using analysis of variance with herbicide treatments and time (WAA) as factors. Herbicide programs were analysed separately for PRE, POST and PRE followed by POST applications for both field trials to determine efficacy of naked crabgrass control. The means of significant source effects (main effects and interactions) of all trials were compared using Fisher's Protected LSD at the 5% significance level. All data were analysed using Genstat 13th edn. VSN International Ltd. (Payne, 2011).

6.3. Results

6.3.1. Experiment 1: Greenhouse trial

Seedling emergence in the control treatments of large crabgrass was only slightly higher on sandy soil compared to clay soil. Naked crabgrass emergence was similar on both soil types. Both naked and large crabgrass showed three distinct emergence peaks on clay soil, but only two on sandy soil (Figure 6.1). Naked crabgrass started to emerge in control treatments in both soil types within seven days of planting, while large crabgrass took up to 11 days to emerge.

127
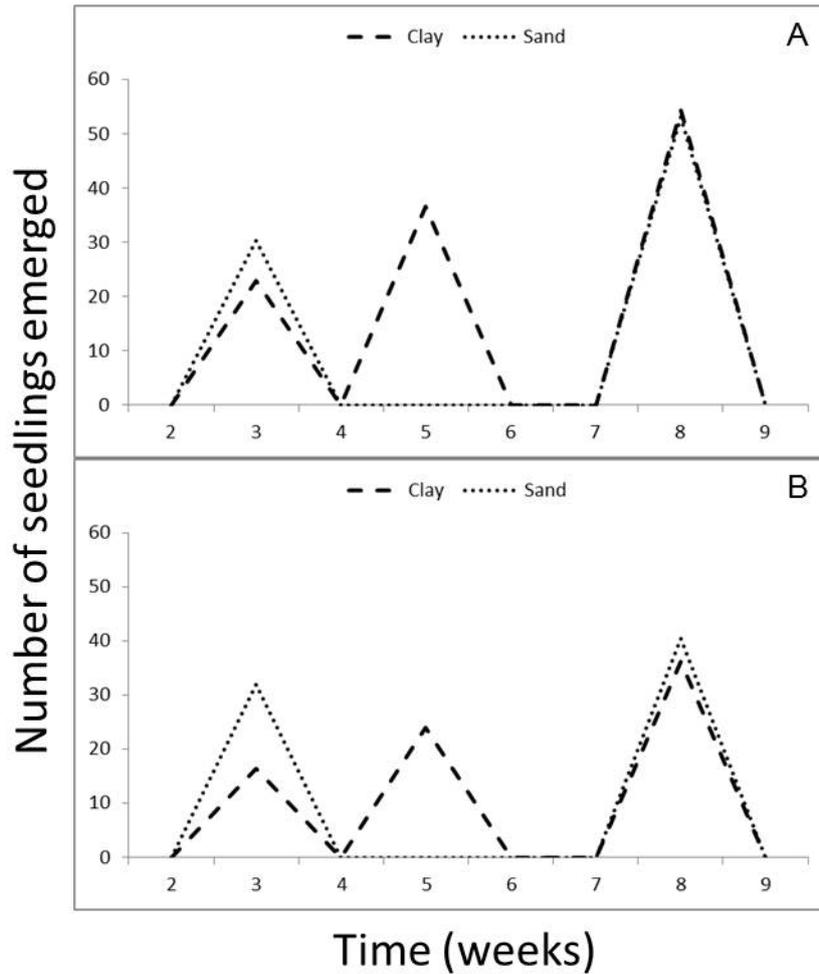
Figure 6.1. Emergence patterns over eight weeks of A) naked crabgrass and B) large crabgrass on two soil types.

Control of naked and large crabgrass did not differ significantly between herbicide treatments and was on average 74 and 94%, respectively. Soil type was highly significant with regard to control of both naked ($F=112.03$, $P<0.001$) and large crabgrass ($F=64.45$, $P<0.001$). Control of naked crabgrass was significantly better on clay soil compared to control on sandy soil. No significant interactions between soil type, herbicide treatments and time after application (WAA) were recorded for control of naked crabgrass. Naked crabgrass control was less in acetochlor treatments compared to s-metolachlor on sandy soil, but not on clay soil. Naked crabgrass was effectively controlled for up to 4 WAA on clay soil and seedlings started to emerge 7 WAA. Emergence of naked crabgrass seedlings started 2 WAA on sandy soil and

128

poor control of 52% was recorded (Figure 6.2 A). The interactions between soil type, herbicides treatments and time after application (WAA) were highly significant with regard to control of large crabgrass (F=9.14, P<0.001). Large crabgrass seedlings started to emerge in both treatments on clay loam soil 7 WAA. On sandy soil large crabgrass started to emerge in s-metolachlor treatments 3 WAA (6%) and 4 WAA (3%) in acetochlor (840 g.l^{-1}) treatments. Control of large crabgrass was however, effective for up to 7 WAA and declined by 10% 8 WAA on clay soil where s-metolchlor was applied. Acetochlor showed the greatest decrease in control of large crabgrass (33%) on sandy soil 8 WAA. Seedling emergence of large crabgrass was greater in acetochlor (840 g.l^{-1}) treatments (36%) compared to s-metolachlor treatments (14%), 8 WAA (Figure 6.2 B).
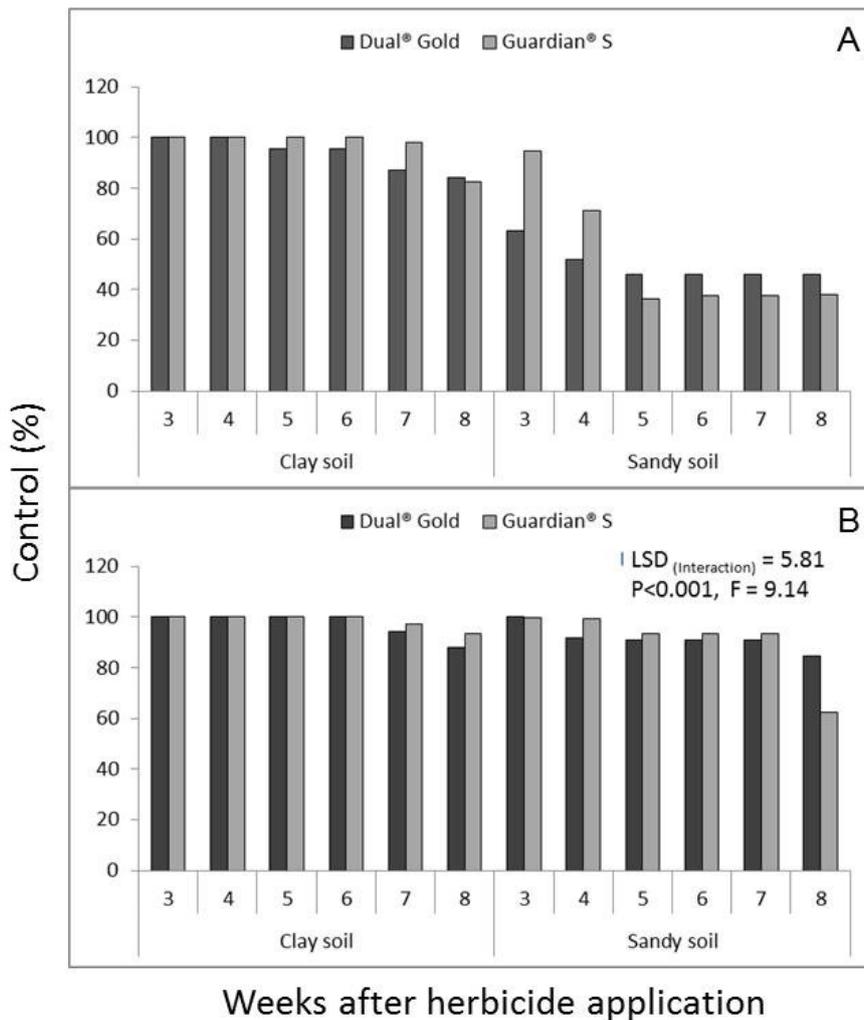
Figure 6.2. The efficacy of Guardian® S (acetochlor) and Dual® Gold (s-metolachlor) on control of A) naked crabgrass and B) large crabgrass on two soil types. (Interaction for naked crabgrass was not significant)

6.3.2. Experiment 2: Field trial 1

The efficacy (% control) of three herbicide programs (nine treatments) tested in the field 3 and 8 WAA is summarized in Table 6.2. Similar results with regard to the application of PRE herbicides were found in the field trial where no significant differences between PRE herbicides for naked crabgrass control were observed. The first seedlings emerged in plots between 16 and 19 days after acetochlor application (700 and 840 g.l^{-1} formulations) and 23 days after s-metolachlor were applied. The average naked crab grass control over all the

130

treatments were 62% 3 WAA and reduced to 50% 8 WAA. Efficacy differed significantly between POST herbicides where paraquat and glyphosate gave control of less than 43% compared to glyphosate/mesotrione/s-metolachlor (72%). Control of naked crabgrass (average of all the treatments) reduced significantly to 36% 8 WAA in the once-off POST applications. Effective control was recorded for all treatments in the PRE followed by POST programs but the s-dimethenamid followed by dicamba/topramezone treatment gave the worst control namely 87%. Naked crabgrass seedlings started to emerge 33, 44 and 51 days after the application of POST dicamba/topramezone, tembotrione + atrazine and mesotrione + atrazine/s-metolachlor, respectively.

131

Table 6.2. Effect of nine herbicide applications on the percentage control of naked crabgrass in a field trial (no crop planted) at two, three and eight weeks after herbicide application.

Herbicide programs		Control (%)		
		WAA[a]		Mean
PRE application		3[b]	8	
acetochlor (700)		57.53	44.00	50.77
s-metolachlor (915)		73.29	55.5.	64.39
acetochlor (840)		56.16	50.00	53.08
	Mean[2]	62.33	49.83	
POST application		2[c]	8	
paraquat (200)		45.89	0	22.95a
glyphosate (250a.e[d].)/ mesotrione (25)/ s-metolachlor (250)		77.40	66.00	71.70b
glyphosate (450a.e.)		43.84	40.50	42.17a
	Mean	55.71a	35.50b	
PRE fb[d] POST application		2[c]	8	
s-metolachlor (915) +mesotrione (480) fb atrazine (370)/s-metolachlor (290) + mesotrione		100.00	100.00	100.00b
acetochlor (840) fb tembotrione (420) + atrazine (500) + Ballista		95.89	96.58	96.23ab
s-dimethenamid (720) fb dicamba(160) / topramezone (50) +Dash		89.73	84.93	87.33a
	Mean	95.21	93.84	

[a]WAA = Weeks after application, [b] 3 and 8 weeks after PRE. [c] 2 and 8 weeks after POST, [d]fb = Followed by, [c] = acid equivalent. Means followed by different letters in a column or row differ significantly at P=0.05 according to Fisher's protected LSD.

Herbicide treatments significantly affected the growth (mean % cover over time) of naked crabgrass in the once-off PRE and POST programs. Plots treated with acetochlor (both

132

formulations) had grass cover of greater than 70% compared to plots treated with s-metolachlor (61%). Where paraquat was applied, plots had the highest grass cover (89%) followed by plots where glyphosate (540 g a.e.) was applied (74%). Mean cover of naked crabgrass in the PRE herbicide treatments increased to 89% when grasses were physiologically matured (11 WAA). The same tendency was observed where POST herbicides were applied only once. In the PRE followed by POST spray programme, emergence of naked crabgrass seedlings was reduced by 85% after the POST applications and grass cover only reached 7% 11 WAA in these treatments (Figure 6.3).

133
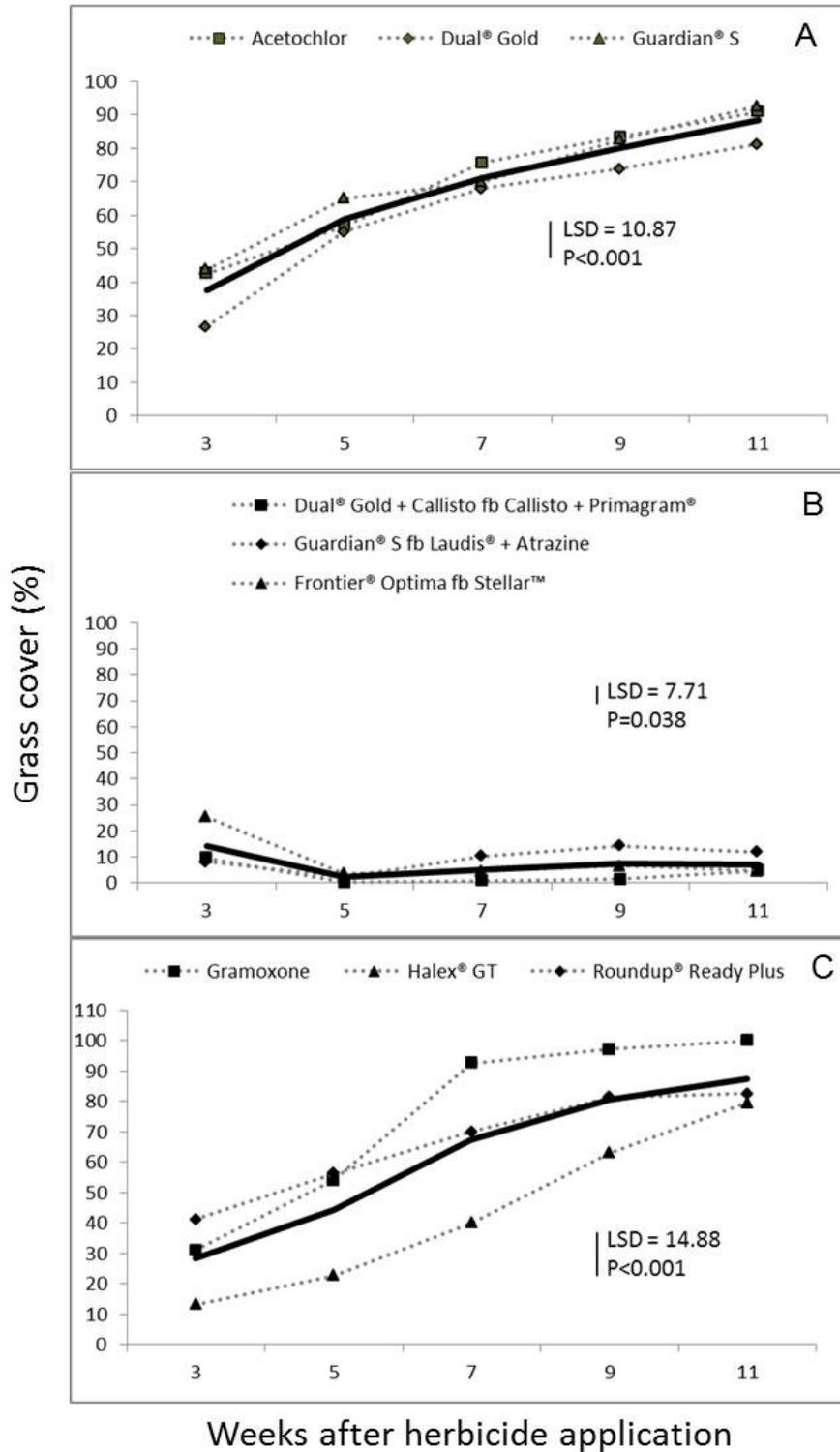
Figure 6.3. Increase in naked crabgrass growth (% cover) after herbicide applications in three herbicide programs, A) PRE, B) PRE followed by POST and C) POST. (Solid line indicates mean growth)

134

Plant height and dry mass of naked crabgrass for each herbicide and control treatments is listed in Table 6.3. Both parameters did not differ significantly between control treatments and applications of once-off PRE and POST herbicides indicate severe infestations.

Table 6.3. Plant height and dry biomass of naked crabgrass in pre- (PRE) and post-emergence (POST) herbicide spray programs recorded at eight weeks after grass emergence in a field trial (no crop planted).

	Herbicide treatments	Plant height (cm)	Biomass (g)
	Control	83.02b	42.51b
PRE	acetochlor (700)	66.56b	37.67b
	s-metolachlor (915)	73.88b	38.19b
	acetochlor (840)	57.59b	29.55b
POST	paraquat (200)	81.18b	41.84b
	glyphosate (250a.e[b].)/ mesotrione (25)/ s-metolachlor (250)	53.95b	28.1b
	glyphosate (450a.e.)	77.94b	40.47b
PRE fb[a] POST	s-metolachlor (915) +mesotrione (480) fb atrazine (370)/s-metolachlor (290) + mesotrione	0a	0a
	acetochlor (840) fb tembotrione (420) + atrazine (500) + Ballista	19.04a	9.89a
	s-dimethenamid (720) fb dicamba(160) / topramezone (50) +Dash	16.02a	8.51a

[a]fb = followed by, [b] = acid equivalent. Means within columns followed by different letters differ significantly at P=0.05.

135

6.3.3. Experiment 3: Field trial 2

Naked crabgrass seedlings started to emerge in maize plots 17 days after the respective once-off application of acetochlor (700 and 840 g.l^{-1} formulations) and 24 days after s-metolachlor. Where the once-off POST herbicides were applied, paraquat treated plots showed emergence 14 days after application and 35 days after application of glyphosate/mesotrione/s-metolachlor and glyphosate (540 g a.e.) treatment plots. The mean percentage cover of naked crabgrass did not differ between PRE herbicides and showed a mean grass cover of 37%. Similar results were obtained where POST herbicide was applied and a mean grass cover of 30% was recorded. No grass emergence was observed in plots where PRE herbicides were followed by POST herbicide applications for the duration of the season. The efficacy of all herbicide treatments evaluated to control naked crabgrass in maize is shown in Table 6.4. Efficacy (% control) was significantly different between herbicide treatments and time (WAA) only for the POST spray programs where paraquat gave significantly less control. Control of naked crabgrass with only PRE herbicides was 85%, while the PRE followed by POST spray programme was the most effective (100%).

136

Table 6.4. Effect of nine herbicide applications on the percentage control of naked crabgrass at four and eight weeks after herbicide application in a field trial planted with maize.

Herbicides programs	Control (%)		
	WAA[a]		Mean
PRE application	4[b]	8	
acetochlor (700)	88.8	83.8	86.2
s-metolachlor (915)	78.8	76.2	77.5
acetochlor (840)	87.5	87.5	87.5
Mean	85	82.5	
LSD(Interaction)	ns		
PRE fb[c] POST applications			
s-metolachlor (915) +mesotrione (480) fb atrazine (370)/s-metolachlor (290) + mesotrione	99.5	100	99.75
acetochlor (840) fb tembotrione (420) + atrazine (500) + Ballista	100	99	99.5
s-dimethenamid (720) fb dicamba(160) / topramezone (50) +Dash	100	99.5	99.75
Mean	99.83	99.5	
LSD(Interaction)	ns		
POST applications			
paraquat (200)	43.75a	8.75a	26.25
glyphosate (250a.e[b].)/mesotrione (25)/ s-metolachlor (250)	100.00b	99.50b	99.75
glyphosate (450a.e.)	100.00b	93.75b	96.88
Mean	81.25a	67.33b	
LSD(Interaction)	5.36		

[a] WAA = Weeks after application, [b] = Application of PRE at four and eight WAA as well as for POST application, [c] fb = Followed by, [d]=acid equivalent. Means followed by different letters in a column or row differ significantly at P=0.05 according to Fisher's protected LSD

137

Maize yielded 2.83 t.ha^{-1} in clean control plots compared to the 1.00 t.ha^{-1} in the weedy control plots, indicating a 64% yield loss. A similar trend was observed for all yield variables, expressed as a percentage of the clean control with regard to herbicide treatments (Table 6.5). Maize yield was 50% lower in plots treated with a once-off application of acetochlor (840 g.l^{-1}) and the once-off POST application of paraquat, respectively. The highest yield was recorded where PRE herbicides were followed by POST herbicide application and for the POST where glyphosate/mesotrione/s-metolachlor was applied.

138

Table 6.5. Yield data expressed as a percentage of the control treatment for nine herbicide applications.

Herbicides treatments	% of control		
	Ear mass	Total kernel weight	Yield (t.ha^{-1})
Clean control	100.00	100.00	100.00
Weedy control	33.09	33.48	35.48
acetochlor (700)	92.93	93.57	99.15
s-metolachlor (915)	45.42	44.69	47.36
acetochlor (840)	74.79	76.12	80.66
s-metolachlor (915) +mesotrione (480) fb atrazine (370)/s-metolachlor (290) + mesotrione	128.10	128.09	136.80
acetochlor (840) fb tembotrione (420) + atrazine (500) + Ballista	96.72	96.07	101.80
s-dimethenamid (720) fb dicamba(160) / topramezone (50) +Dash	138.65	143.9	152.48
paraquat (200)	49.23	48.39	51.28
glyphosate (250a.e[b].)/mesotrione (25)/ s-metolachlor (250)	119.82	120.25	127.43
glyphosate (450a.e.)	73.51	70.17	74.36
LSD$_{(Herbicide\ treatments)}$	57.72	56.09	59.95

[a]fb = followed by, [b]=acid equivalent

6.4. Discussion

According to international standards and Agro-chemical companies in South Africa weed control between 90 and 100% is commercially acceptable (effective), between 50 and 89% is reduced or suppressed control, while control less than 50% is not commercially acceptable. Control of large crabgrass with both treatments was commercially acceptable on both sandy

139

and clay soil, but acetochlor (840 g.l^{-1}) showed a decrease in residual effect sooner than s-metolachlor. Naked crabgrass showed significantly more tolerance to both acetochlor and s-metolachlor on sandy soil and control was not commercially acceptable. Soil characteristics have a profound effect on herbicide persistence and activity in soil, influencing efficacy of soil applied herbicides significantly (Rao, 2000). Clay particles, organic matter and soil water content are but a few factors affecting the adsorption and availability of herbicides in the soil. However, organic matter in soil has a greater effect on the sorption coefficient of acetanilide herbicides especially for acetochlor and s-metolachlor than clay content (Vasilakoglou et al., 2001, Wang et al., 1999). Contrarily James and Rahman (2009) concluded that soil organic content has little influence on the activity of asetanilide herbicides such as acetochlor, s-metolachlor, alachlor and dimethenamid. The organic matter content of South African soils is however, very low (<1%), but soils with higher clay content tend to contain more organic matter retaining higher herbicide concentrations which in combination could explain the better control in clay soils. Furthermore, clay content is positively correlated with the sorption coefficient, while sand content showed a negative correlation for s-metolachlor (Bedmar et al., 2011).

In this study similar results as recorded on sandy loam soil were, however, found in field trials for the control of naked crabgrass on a clay loam soil with regard to acetochlor (700 and 840 g.l^{-1}) and s-metolachlor. Under field conditions herbicides are influenced by several environmental conditions and can leach or break down more rapidly compared to controlled environments. These interactions between environment and herbicide activity or persistence could attribute to results in the field trial where acetochlor and s-metolachlor did not give effective naked crabgrass control on a heavier clay loam soil. Residual activity of most acetanilide herbicides range between six to 14 weeks after application (Rao, 2000; James and Rahman, 2009), but this was not nearly achieved for naked crabgrass in this study. Cao et al. (2008) recorded a sharp decline in s-metolachlor in soil 21 days after application as was the case in these field trials where naked crabgrass started to emerge between 16 to 22 days

140

after acetochlor and s-metolachlor applications. Although seedling emergence was initially low compared to control treatments, one large crabgrass plant can produce up to 180 000 seeds and this may lead to a significant increase in late emerging seedlings and seed numbers in soilbanks (Hilgenfeld, 2004). Continuous use of herbicides that do not give effective control for grass infestations will stimulate infestation levels in the long-term (Johnson and Coble, 1986). Naked crabgrass seeds germinating later in the season are problematic and can cause severe yield reductions in maize [See also Chapter 5].

The use of POST herbicides to control grasses is increasing gradually in maize producing areas in South Africa, since Halex GT (Syngenta), Laudis® (Bayer) and Stellar™ (BASF) was registered for early POST grass control in maize during 2010. The increase in planting Roundup® Ready tolerant cultivars where glyphosate can be applied also stimulated the shift towards POST herbicide applications. Where naked crabgrass could grow without any competition or canopy effect of a crop, a single POST application of herbicides could, however, not control naked crabgrass effectively. The effect of re-emerging seedlings throughout the season due to escape from the first application can pose a serious threat where severe infestations of naked crabgrass are experienced. Effective control was however achieved for naked crabgrass in the second field trial where glyphosate and glyphosate/mesotrione/s-metolachlor were applied in the presence of maize. Control of giant foxtail grass was reported to be variable with only one POST application of glyphosate and best control was received where initial glyphosate application was followed by an application two to three weeks later (Gower et al., 2002, Parker et al., 2004). The timing of POST application is crucial and if grass weeds are too tall or rainfall delays application, weed infestation levels could increase exponentially and can influence crop yield negatively (Myers et al., 2005).

In both field trials naked crabgrass control was most effective in the herbicide spray programs where PRE herbicides were followed by a POST herbicide application. The few naked crabgrass plants in these plots was significantly stunted and failed to produce

141

inflorescences within 10 weeks after emergence, confirming the residual efficacy of triketone herbicides with active ingredients tembotrione and mesotrione (Gatzweiler et al., 2012, Rouchard et al., 2000). Naked crabgrass has the ability to form a thick carpet-like growth pattern within weeks after emergence making it difficult to control late in the season. Even if low numbers of seedlings emerged, the probability of rapid colonization by naked crabgrass tufts between maize rows will ensure significant yield losses due to the competition effect. [See also Chapter 4]. Late infestation levels of naked crabgrass is also difficult to control since maize can be too tall to permit cultivation and POST herbicide application with high-rise sprayers will be the only option.

This study indicated that a shift from predominantly large crabgrass infestations to increased naked crabgrass infestations could be the reason for reports of poor control of *Digitaria* spp., due to the more tolerant nature of naked crabgrass towards commonly used herbicides. Large crabgrass does not form a persistent seed bank when effectively controlled and the closely related southern crabgrass rarely persists more than one year in soil (Kobayashi and Oyanagi, 2005; Norsworthy, 2008). Large crabgrass can still be effectively controlled with acetochlor and s-metolachlor registered in maize, but naked crabgrass showed increased tolerance to these herbicides and escapes control more easily to give rise to subsequent emergence later in the growing season. In areas where naked crabgrass has been positively identified, effective control will only be achieved with PRE herbicides followed by POST herbicide application of the triketone group, three to four weeks after planting to prevent significant yield losses.

CHAPTER 7

GENERAL DISCUSSION

Literature regarding the biology and weed status of naked crabgrass (*Digitaria nuda* Schumach.) is lacking world-wide. This study was, therefore, aimed at determining factors that influence seed germination and plant growth, to quantify its competitive abilities and to find methods for effective control of naked crabgrass in maize production.

Germination characteristics of naked crabgrass, which were determined in greenhouse trials in this study, showed some similarities to those reported for large crabgrass, but subtle differences regarding temperature and soil type could be distinguished. Naked crabgrass germinated best at both fluctuating temperature regimens of 15/30 °C and constant temperature above 25 °C. Halvorson and Guertin (2003) compiled an extensive factsheet of large crabgrass and the optimum germination temperature ranges concur with those of naked crabgrass. Crabgrass species are abundant seed producers (i.e. 170 000 per plant) and knowledge of germination characteristics can assist in the implementation of an integrated weed management control strategy (Chauhan and Johnson, 2010, Hartzler et al., 1999; Mitich, 1988). Areas where severe naked crabgrass infestations prevailed, experience moderate to high temperatures during the crop growing season. Fluctuations between maximum and minimum temperatures can favour the germination of naked crabgrass as has been reported for several annual grass weed species (Nishimoto and McCarty, 1997; Steinmaus et al., 2000). Several taxonomic references are available for the description and occurrence of naked crabgrass (Barkworth et al. 2003; Clayton and Renvoize, 1982; Launert And Pope, 1989; Webster, 1983), but no results on factors affecting germination and growth could be found. Factors affecting germination and emergence have been well documented, however, for the closely related large crabgrass (*Digitaria sanguinalis* (L.) Scop.), while

143

morphological growth parameters of naked crabgrass had been only compared to Southern crabgrass (Souza et al., 2012).

The natural or inherent dormancy exhibited by grass species complicate the timely control and management of the soil seedbank for grass weeds (Gardner, 1996). Naked crabgrass also exhibited dormancy and very low germination percentages were recorded with fresh seed compared to 1 year old seed, emphasising the need for effective control before seed shedding. The particular mechanisms involved in the dormancy of naked crabgrass have yet to be determined. Soaking (priming or imbibition) of naked crabgrass seed in water possibly removed putative inhibitors, since the highest germination percentages was recorded where fresh seed was pre-soaked in distilled water (Baskin and Baskin, 2004; Gallart et al., 2010). Survival of weed seed in soil is, however, more important than the actual germination percentages attained (Monaco et al., 2002). Seed germination and competitive ability of naked crabgrass was significantly influenced by soil type. The present study indicated faster emergence and substantial higher dry biomass of naked crabgrass on clay loam soil, in contrast with large crabgrass that prefers more sandy soil (Halvorson and Guertin, 2003). However, these results, recorded under controlled conditions, should not be misconstrued as to the potential of naked crabgrass prevalence on a vast range of soils (Kok et al., 1989). Similar to large crabgrass, naked crabgrass seed is small and light weight, remaining mostly on or near the soil surface and seedlings do not emerge from a soil depth greater than 6 cm. The difficulty with annual crabgrass weed species manifests in the number of seeds produced by each plant. High seed numbers will ensure prevalence in the soil seedbank, even if less than 50% of seeds are viable over a period of three years (Biswas et al., 1978; Halvorson and Guertin, 2003).

Above-ground morphology of naked crabgrass displays a more robust-type of growth compared to large crabgrass, indicating possible superior competitive abilities (personal observation). Souza et al. (2012) compared growth rates between naked crabgrass and Southern crabgrass, where the latter had significantly higher values, measured for leaf area,

144

leaf and tiller number and dry biomass per plant. Several experimental designs are used to investigate and interpret competitive abilities and aggressivity levels of plant species, unfortunately not one without limitations and possible misinterpretation of results (Gibson et al., 1999; Weigelt and Joliffe, 2000). A simple replacement series, best describing and/or comparing competitive abilities between two plant species, indicated equal competitiveness and aggressivity for naked crabgrass and large crabgrass, when in full competition. The respective competitive indices, used in this study (CR, AI, RYT and RCC) could quantify the competition effect, aggressivity and demands for limiting resources, for both naked crabgrass and large crabgrass, emphasizing their strong competitiveness. These calculated values can be useful in establishing a hierarchy of competitiveness between related grass weeds and even between different grass species, assisting producers to prevent and minimize crop yield losses. The competition effect on crops and possible yield losses due to infestation by naked crabgrass has not previously been reported.

To date little attempt has been made to assess crop yield losses due to infestations of rather unknown *Digitaria* species. Several crop loss models can be used to quantify the effect of weed density on crop losses (Cousens, 1985; Kropff and Spitters, 1991). Estimated yield loss values predicted by the hyperbolic regressions model (Cousens, 1985) when maize was in competition with either naked crabgrass or large crabgrass, concurred with observed values. These results were obtained in separate greenhouse trials to exclude contamination of the species, but should however be verified under field conditions. The empirical model of Kropff and Spitters (1991) was used to determine a damage coefficient (q), using calculated values of the total share in above-ground biomass of the respective grass species and maize. Higher q-values were recorded for large crabgrass on both soil types. A significantly higher q-value for naked crabgrass was only recorded on sandy soil, emphasising the subtle growth preferences between the two grass weeds. Maize yield was reduced by more than 50% when the density was app. 50 grasses per m^2 and was estimated to be as high as 76% for large crabgrass on clay soil and 29% for naked crabgrass on sandy soil.

145

Naked crabgrass infestations are increasing in the central maize production area of South Africa and poor control with herbicides registered on maize to effectively control large crabgrass can lead to the predominance of this grass weed. Since no data are available on the critical period of crabgrass control in maize production under South African conditions and soils, herbicide applications can be ineffective. This could mean that a proportion of a naked crabgrass population can "escape" chemical control, explaining the "poor" control. Another scenario could also be that naked crabgrass tufts are too big for effective POST control, indicating "tolerance" to herbicides. It was therefore necessary to define the critical period of naked crabgrass control, reducing the interference of grass infestations and preventing critical yield losses. Three field studies, two conducted on clay loam soil and the third on sandy soil, indicated that season-long control is necessary when naked crabgrass infestations is high early in the season. Yield loss was also experienced when maize was planted later and infestation levels increased during the latter part of the growth cycle of maize. As demonstrated by Saayman-Du Toit and Le Court De Billot (1991), season-long germination of large crabgrass seeds can cause severe competition with maize, making early season control necessary. The beginning, duration and ending of CPWC for naked crabgrass was strongly dependent on environmental conditions, corresponding with previous results for CPWC determined for maize (Evans et al., 2003a; Isik et al., 2006; Knezevic et al., 2002, Page at al., 2009).

The most significant difference between naked crabgrass and large crabgrass was observed with regard to susceptibility to herbicides. As mentioned before, poor control has been recorded for certain PRE herbicides (mostly acetochlor and s-metolachlor), and naked crabgrass was found to be significantly more tolerant to these herbicides when their efficacy was evaluated under controlled conditions. Nine herbicide spray programs were tested in two field trials and the most effective control of naked crabgrass was achieved by PRE applications followed by POST application of active ingredients in the triketone group. Grass weeds are predominantly controlled by graminicides in the acetanilide group (Alleman and

146

Mphundi, 2010; Myers et al., 2005) and POST herbicides for the control of grass weeds were only recently registered on maize. The competitive ability of naked crabgrass is severe and has been established in this study, making POST applications critical to minimize interference of this grass weed. Timely applications of POST herbicides are crucial for effective control and it appears that producers usually wait too long before application, resulting in the re-growth of grass tufts.

This study presented critical results on the biology and competiveness of naked crabgrass which could help maize producers in their decision making processes to achieve effective grass weed control. A preliminary prediction model could determine the relative yield loss of maize when certain naked crabgrass and large crabgrass densities prevail, establishing the weed status of naked crabgrass. Due to the similarities in morphological growth of naked crabgrass and large crabgrass and with the shift to minimum tillage, incorporated into conservation agricultural systems, POST herbicides such as Laudis® (tembotrione), Stellar™ L (topramezone) and Callisto (mesotrione) will be more effective in controlling these grass weeds.

Naked crabgrass showed similar characteristics to the closely related large crabgrass with regard to germination temperature preferences and burial depth, as indicated by this study and literature references. However, naked crabgrass preferred clay soil to sandy soil, and was significantly more competitive on clay soil. Although naked crabgrass displayed more tolerance to acetanilide herbicides on clay soil as well, effective control could not be achieved with application of these herbicides only. Since both grass weed species need season-long control, as indicated by the high maize yield losses in weedy control treatments, soil type and POST herbicide selection will be significant factors influencing the effective control of naked crabgrass. In a conservation agriculture system, less or zero tillage form part of the successful implementation of such a system and may lead to more suitable conditions for both naked and large crabgrass infestations. According to infestation levels farmers implementing

147

conservation agriculture should consider that an increase in reliance on multiple POST herbicides applications will be necessary for effective control.

REFERENCES

Aerts, R., Boot, R.G.A., Van der Aardt, P.J.M., 1991. The relationship between above- and belowground biomass allocation patterns and competitive ability. Oecologia, 87:551-559.

Aguyoh, J.N., Masiunas, J.B., 2003. Interference of large crabgrass (*Digitaria sanguinalis*) with snap beans. Weed Science, 51:171–176.

Allemann, J., Mphundi, P.M., 2010. Screening of some South Africa maize (*Zea mays* L.) cultivars for acetochlor tolerance. South African Journal Plant and Soil, 27:235-241.

Aminpanah, H., Javadi, M., 2011. A replacement series evaluation of competition between rice (*Oryza sativa* L.) and rice barnyardgrass (*Echinichloa oryzicola* Vasing). Scientific Research and Essays, 6:5065-5071.

Anderson, R. L., 2000. Ecology and interference of Proso Millet (*Oanicum miliaceum*) in Semi-Arid Corn. Weed Technology, 14:45-50.

Barkworth, M.E., Capels, K.M., Long, S., Piep, M.B., 2003. Flora of North America. Vol 25. Magnoliophyta: Commelinidae (in part): Poaceae, Part 2. NY Oxford, Oxford University Press.

Baskin, J.M., Baskin, C.C., 2004. A classification system for seed dormancy. Seed Science Research, 14:1-16.

Bauer, T. A., Mortensen, D. A., 1992. A comparison of economic and economic optimal thresholds for two annual weeds in soybeans. Weed Technology, 6:228-235.

Bedmar, F., Daniel, P.E., Costa, J.L., Giménez, D., 2011. Sorption of acetochlor, s-metolachlor, and atrazine in surface and subsurface soil horizons of Argentina. Environmental Toxicology and Chemistry, 30:1990-1996.

Benvenuti, S., Macchia, M., Miele, S., 2001. Quantitative analysis of emergence of seedlings from buried weed seeds with increasing soil depth. Weed Science, 49:528-535.

149

Bernards, M. L., Simmons, J.T., Guza, C.J., Schulz, C.R., Penner, D., Kells, J.J., 2006. Inbred corn response to acetamide herbicides as affected by safeners and microencapsulation. Weed Technology, 20:458-465.

Bhowmik, P.C., Kushwaha, S., Mitra, S., 1999. Response of various weed species and corn (*Zea mays*) to RPA 201772. Weed Technology, 13:504-509.

Biswas, P.K., Devi, A., Roy, P.K., Paul, K.B., 1978. Enzyme activity in dormant and non-dormant large crabgrass (*Digitaris sanguinalis*) seeds following hydration. Weed Science, 26:90-93.

Bosnic, A.C., Swanton, C.J., 1997. Influence of barnyardgrass (*Echinochloa crus-galli*) time of emergence and density on corn (*Zea mays*). Weed Science, 45:276-282

Botha C, ed 2010. Common weeds of crops and gardens in southern Africa. 2nd ed. ARC-Grain Crops Institute, Potchefstroom and Syngenta, Halfway House. 384 p

Bromilow, C., ed. 2010. Problem plants and alien weeds of South Africa. 3rd ed. Briza Publications, Pretoria, South Africa. 424p.

Buchanan, G.A., Hoveland, C.S., Harris, M.C., 1975. Response of weeds to soil pH. Weed Science, 23:473-477.

Buhler, D.D., 1992. Population dynamics and control of annual weeds in corn (*Zea mays*) as influenced by tillage systems. Weed Science, 40:241-248.

Cahill, J.F. Jr., 1999. Fertilization effects on interaction between above- and belowground competition in an old field. Ecology, 80:446-480.

Cahill, J.F. Jr., 2002. Interactions between root and shoot competition vary among species. Oikos, 99:101-112.

Cao, P., Wang, X., Liu, F., Zhao, E., Han, L., 2008. Dissipation and residue of s-metolachlor in maize and soil. Bulletin of Environmental Contamination and Toxicology, 80:391-394.

Cathcart, R.J., Swanton, C.J., 2004. Nitrogen and green foxtail (*Setaria viridis*) competition effects on corn growth and development. Weed Science, 52:1039-1049.

Cerrudo, D., Page, E.R., Tollenaar, M., Stewart G., Swanton, C.J., 2012. Mechanisms of yield loss in maize caused by weed competition. Weed Science, 60:225-232.

150

Chauhan, B.S., Gill, G., Preston, C., 2006. Influence of environmental factors on seed germination and seedling emergence of Oriental mustard (*Sisymbrium orientale*). Weed Science, 54:1025-1031.

Chauhan, B.S., Johnson, D.E., 2008a. Germination ecology of Goosegrass (*Eleusine indica*): An important grass weed of rainfed rice. Weed Science, 56:699-706.

Chauhan, B.S., Johnson, D.E., 2008b. Germination ecology of southern crabgrass (*Digitaria ciliaris*) and India crabgrass (*Digitaria longiflora*): Two important weeds of rice in the tropics. Weed Science, 56:722-728.

Chauhan, B.S., Johnson, D.E., 2009. Germination ecology of spiny (*Amaranthus spinosus*) and slender amaranth (*A. viridis*): Troublesome weeds of direct-seeded rice. Weed Science, 57:379-385.

Chauhan, B.S., Johnson, D.E., 2010. Relative importance of shoot and root competition in dry-seeded rice growing with junglerice (*Echinochloa colona*) and Ludwigia (*Ludwigia hyssopifolia*). Weed Science, 58:295-299.

Chikoye, D., Manyong, V.M., Ekeleme, F., 2000. Characteristics of speargrass (*Imperata cylindrica*) dominated fields in West Africa: crops, soil properties, farmer perceptions and management strategies. Crop Protection, 19:481-487.

Chippindall, L.K.A. 1955. The grasses and pastures of South Africa. Part I. A guide to the identification of grasses in South Africa. Central News Agency.

Chism, W.J., Bingham, S.W., 1991. POST control of large crabgrass (*Digitaria sanguinalis*) with herbicides. Weed Science, 39: 62-66.

Clayton, W.D., Renvoize, S.A., 1982. Gramineae: *Digitaria*. In: Flora Tropical East Africa, Part 3, pp. 619-655.

Coffman, C.B., Frank, J.R., 1992. Corn-weed interactions with long-term conservation tillage management. Agronomy Journal, 84:17-21.

Connolly, J. 1987. On the use of response models in mixture experiments. Oecologia, 72: 95-103.

151

Corbett, J.L., Askew, S.D., Thomas, W.E., Wilcut, J.W., 2004. Weed efficacy evaluations for bromoxynil, glufosinate, glyphosate pyrithiobac and sulfosate. Weed Technology, 18:443-453.

Cousens, R., 1985. A simple model relating yield loss to weed density. Annals of Applied Biology, 107:239-252.

Cousens, R.D., O'Neill, M. 1993. Density dependence of replacement series experiments. Oikos 66: 348-352

Culpepper, A.S., Gimenez, A.E., York, A.C., Batts, R.B., Wilcut, J.W., 2001. Morningglory (*Ipomoea* spp.) and large crabgrass (*Digitaria sanguinalis*) control with glyohosate and 2,4-DB mixtures in glyphosate resistant soybean (G*lycine max*). Weed Technology, 15:56-61.

Culpepper, A.S., York, A.C., Jennings, K.M., Batts, R.B., 1998. Interaction of bromoxynil and postemergence graminicides on large crabgrass (*Digitaria sanguinalis*). Weed Technology, 12:554-559.

Davis, A.S., Renner, K.A., Gross, L.K., 2005. Weed seedbank and community shifts in a long-term cropping system experiment. Weed Science, 53:296-306.

Deen, W., Cousens, R., Warringa, J., bastiaans, L., Carberry, P., Rebel, K., Riha, Murphi, C., Benjamin, L. R., Cloughley, C., Cussans, J., Forcella, F., Hunt, T., Jamieson, P., Lindquist, J., Wang, E., 2003. Evaluation of four crops: weed competition models using a common data set. Weed Research, 43:116-129

Dias, N.M.P., Pereira, M.R.D.B., Lopez-Ovejero, R.F., Christoffoleti, P.J., Barela, J.F., Tornisielo, V.L., 2005. Population dynamics of *Digitaria* spp. submitted to selection pressure by herbicides in sugarcane crop. Journal of Environmental Science and Health, B40:21-28.

Dorado, J., Sousa, E., Calha, I.M., González-Andújar, J.L., Fernández-Quintanilla, C. 2009. Predicting weed emergence in maize crops under contrasting climatic conditions. Weed Research, 49: 251-260.

Doub, J.P., Wilson, H.P., Hines, T.E., Hatzios, K.K., 1988. Consecutive annual applications of alachlor and metolachlor to continuous no-till corn (*Zea mays*). Weed Science, 36:340-344.

Elwali, A.M.O., Gascho, G.J., Sumner, M.E., 1985. DRIS norms for 11 nutrients in corn leaves. Agronomy Journal, 77:506-508.

Evans, S.P., Knezevic, S.Z., Lindquist, J.L., Shapiro, C.A., Blakenship, E.E., 2003a. Nitrogen application influences the critical period for weed control in corn. Weed Science, 51:408-417

Evans, S.P., Kezevic, S.Z., Lindquist, J.L., Shapiro, C.A., 2003b. Influence of nitrogen and duration of weed interference on corn growth and development. Weed Science, 51:546-556.

Fausey, J.C., Kells, J.J., Swinton, S.M., Renner, K.A., 1997. Giant foxtail (*Setaria faberi*) interference in nonirrigated corn (*Zea mays*). Weed Science, 45:256-260.

Ferrel, J.A., Witt, W.W., 2002. Comparison of glyphosate with other herbicides for weed control in corn (*Zea mays*): Efficacy and economics. Weed Technology, 16:701-706.

Firbank, L.G., Watkinson, A.R., 1985. On the analysis of competition within two-species mixtures of plants. Journal of Applied Ecology, 22:503-517.

Forcella, F., Wilson, R.G., Renner, K.A., Dekker, J., Harvey, R.G., Alm, D.A., Buhler, D.D., Cardina, J., 1992. Weed seedbanks of the U.S. cornbelt: Magnitude, variation, emergence and application. Weed Science, 40:636-644.

Freckleton, R. P., Watkinson, A.R., 1999. The mis-measurement of plant competition. Functional Ecology, 13:285-287.

Freckleton, R.P., Watkinson, A.R., 2000. Designs for greenhouse studies of interaction between plants: an analytical perspective. Journal of Ecology, 88:386-391.

FSSA, Fertilizer Society of South Africa, 2007. Ed. A. J. Buys. 7th edition. 331 p.

Fu, R., Ashley, R.A., 2006. Interference of large crabgrass (*Digitaria sanguinalis*), redroot pigweed (*Amaranthus retroflexus*) and hairy galinsoga (*Galinsoga ciliate*) with bell pepper. Weed Science, 54:364-372.

153

Gallart, M., Mas, M.T., VERDú, A.M.C., 2010. Demography of *Digitaria sanguinalis*: Effect of the emergence time on survival, reproduction, and biomass. Weed Biology Management, 10:132-140.

Galon, L., Agostinetto, D., 2009. Comparison of empirical models for predicting yield loss of irrigated rice (*Oryza sativa*) mixed with *Echinochloa* spp. Crop Protection, 28:825-830.

Gardner, D., 1996. Crabgrass (Digitaria spp.) taxa. Agronomy 517: Weed biology and ecology. http://www.agron.iastate.edu/~weeds/weedBiolLibrary/u4crab1.html

Gantoli, G., Ayala, V.R., Gerhards, R., 2013. Determination of the critical period of weed control in corn. Weed Technology, 27:63-71.

Gatzweiler, E., Krähmer, H., Hacker, E., Hills, M., Trabold, K., Bonfig-Picard, G., 2012. Weed spectrum and selectivity of tembotrione under varying environmental conditions. Julius- Kühn-Archiv, 434:385-391.

Ghosheh, H.Z., Holshouser, D.L., Chandler, J.M., 1996. The critical period of Johnsongrass (*Sorghum halapense*) control in field corn. Weed Science, 44:944-947.

Gibbs, G.E., Watson, R.L., Koekemoer, M., Smook,L., Barker, N.P, Anderson,H.A., Dallwtiz, M.J., 1991. Grasses of Southern Africa. Ed. OA Leistner. Memoirs of the Botanical Survey of South Africa no. 58.

Gibson, D.J., Connolly, J., Harnett, D.C., Weidenhamers J.D., 1999. Designs for greenhouse studies of interaction between plants. Journal of Ecology, 87:1-16.

Gower, S.A., Loux, M.M., Cardina, J., Harrison, S.K., 2002. Effect of planting date, residual herbicide, and POST application timing on weed control and grain yield in glyphosate-tolerant corn (*Zea mays*). Weed Technology, 16:488-494.

Grain South Africa. Production costs for central and northern Free State (2012-13 production year). www.grainsa.co.za, accessed 30/04/2013

Grundy, A.C.,Mead, A., Burston, S., 2003. Modelling the emergence response of weed seeds to burial depth: interaction with seed density, weight and shape. Journal of Applied Ecology, 40:757–770.

Halford, C., Hamill, A.S., Zhang, J., Doucet, C., 2001. Critical period of weed control in no-till soybean (*Glycine max*) and corn (*Zea mays*). Weed Technology, 15:737-744.

Hall, M.R., Swanton, C.J., Anderson, G.W., 1992. The critical period of weed control in grain corn (*Zea mays*). Weed Science, 40:441-447.

Halvorson, W.L., Guertin, P., 2003. Factsheet for: *Digitaria sanguinalis* (L.) Scop. U.S. Geological survey, Southwest Biological Science Centre, University of Arizona.

Hamill, A.S., Knezevic, S.Z., Chandler, K., Sikkema, P.H., Tardif, F.J., Shrestha, A., Swanton, C.J., 2000. Weed control in glufosinate-resistant corn (*Zea mays*). Weed Technology, 14:578-585.

Harbur, M.M., Owen, M.D.K., 2004. Response of three annual weeds to corn population density and nitrogen fertilization timing. Weed Science, 52:845-853.

Harper, J.L., 1977. Substitutive experiments, In: Population biology of plants. New York Academic Press, pp. 255-267.

Hart, S.E., Lycan, D.W., Murphy, J.A., 2004. Use of quinclorac for large crabgrass (*Digitaria sanguinalis*) control in newly summer-seeded creeping bentgrass (*Agrostis stolonifera*). Weed Technology, 18:375-379.

Hartzler, R.G., Buhler, D.D., Stoltenberg, D.E., 1999. Emergence characteristics of four annual weed species. Weed Science, 47:578-584.

Hellwig, K.B., Johnson, W.G., Scharf, P.C., 2002. Grass weed interference and nitrogen accumulation in no-tillage corn. Weed Science, 50:757-762

Hilgenfeld, K.L., Martin, A.R., Mortensen, D.A., Mason, S.C., 2004. Weed management in a glyphosate resistant soybean system: weed species shifts. Weed Technology, 18: 284-291.

Holm, L.G., Plucknett, D.L., Pancho, J.V., Herberger, J.P., 1977. The world's worstweeds: distribution and biology, Malabar, FL: The University Press of Hawaii. 609 p

http://www.biodiversityexplorer.org. Accessed 31/08/2010.

http://www.CropLife.co.za. Accessed 3/03/2011.

http://www.grainsa.co.za. Accessed 7/04/2014.

http://www.posa.sanbi.org. Accessed 31/08/2010.

http://www.weedscience.com. Accessed 14/06/2010.

http://www.HRACglobal.com. Accessed 17 July 2013.

Isik, D., Mennan, H., Bukun, B., Oz, A., Ngouajio, M., 2006. The critical period for weed control in corn in Turkey. Weed Technology, 20:867-872.

James, T.K., Rahman, A.. 2009. Efficacy of PRE herbicides on three annual grass weeds in different soils. New Zeeland Plant Protection, 62:356-362.

Johnson, W.C., Coble, H.D., 1986. Crop rotation and herbicide effects on the population dynamics of two annual grasses. Weed Science, 34:452-456.

Joliffe, P.A., 2000. The replacement series. Journal of Ecology, 88:371-385.

Jones, R. E., Medd, R.W., 2000. Economic thresholds and the case for longer term approaches to population management of weeds. Weed Technology, 14:337-350.

Jooste, J.W., Van Biljon, J.J., 1980. The competition of *Cyperus esculentus* with corn. Crop Production, 9:151-155.

Karim, S.M.R., 2000. Competitive ability of three grass weeds grown in upland direct-seeded rice in Bangladesh. Pakistan Journal of Agricultural Research, 16:24-27.

Kiær, L.P., Weisbach, A.N., Weiner, J., 2013. Root and shoot competition: a meta-analysis. Journal of Ecology, 101:1298-1312.

Kim, T.J., Neal, J.C., Ditomaso, J.M., Rossi, F.S., 2002. A survey of weed scientists' perceptions on the significance of crabgrasses (*Digitaria* spp.) in the United States. Weed Technology, 16:239-242.

King, C.A., Oliver, L.R., 1994. A model for predicting large crabgrass (*Digitaria sanguinalis*) emergence as influenced by temperature and water potential. Weed Science, 42:561-567.

Knezevic, S.Z., Avishek, D., Scott, J., Klein, R.N., Golus, J., 2009. Problem weed control in glyphosate-resistant soybean with glyphosate tank mixes and soil applied herbicides. Weed Technology, 23:507-512.

Knezevic, S.Z., Evans, S.P., Blakenship, E.E., Van Acker, R.C., Lindquist, J.L., 2002. Critical period for weed control: the concept and data analysis. Weed Science, 50:773-786.

Kobayashi, H., Oyanagi, A., 2005. *Digitaria ciliaris*: seed banks in untilled and tilled soybean fields. Weed Biology and Management, 5:53-61.

Kok, P.D.F., 1984. Studies on *Digitaria* (Poaceae). 1. Enumeration of species and synonymy. South African Journal of Botany, 3:184-185.

Kok, P.D.F., Robbertse, P.J., Van Wyk, A.E., 1989. Systematic study of *Digitaria* section *Digitaria* (Poaceae) in southern Africa. South African Journal of Botony, 55: 141-153.

Kropff, M.J., Lotz, L.A.P., Weaver, S.E., Bos, H.J., Wallinga, J., Migo, T., 1995. A two parameter model for prediction of crop loss by weed competition from early observations of relative leaf area of the weeds. Annals of Applied Biology 126:329-346.

Kropff, M. J., Spitters, J. T., 1991. A simple model for crop loss by weed competition from early observations on relative leaf area of the weeds. Weed Research, 31:97-105.

Launert, E., Pope, G.V., 1989. Flora Zambesiaca. Vol. 10, Part 3. Ed. P. Goetghebeur and P. Van der Veken (*Digitaria* spp.). Management committee of contributors to Flora Zambesiaca.

Le Court De Billot, M. R., 1988. Relative interference of some common weeds with maize under controlled conditions. Applied Plant Science, 2:45-48.

Lodge, G.M., 2000. Competition among seedlings of perennial grasses, subterranean clover, white clover, and annual ryegrass in replacement series mixtures. Australian Journal of Agricultural Research, 51:377-383.

Lotz, L.A.P., Christenen, S., Cloutier, D., Fernandez Quintanilla, C., Légére, A., Lemieux, C. Lutman, P.J., Pardo Iglesias, A., Salonen, J., Santtin, M., Stigliani, L., Tei, F., 1996. Prediction of the competitive effects of weeds on crop yields based on the relative leaf area of weeds. Weed Research, 36:96-101.

157

Lucero, D.W., Grieu, P., Guckert, A. 2000. Water deficit and plant competition effects on growth and water-use efficiency of white clover (*Trifolium repens*, L.) and ryegrass (*Lolium perenne*, L.). Plant and Soil, 227: 1-15.

Lutman, P.W.J., Risiott, R., Ostermann, H.P., 1996. Investigations into alternative methods to predict the competitive effects of weeds on crop yields. Weed Science, 44:290-297.

Manley, B.S., Wilson, H.O, Hines, T.E., 2002. Management programs and crop rotations influence populations of annual grass weeds and yellow nutsedge. Weed Science, 50:112-119.

Martinkova, Z., Honek, A., Lukas, J., 2006. Seed age and storage conditions influence germination of barnyard grass (*Echinichloa crus-galli*). Weed Science, 54:298-304.

Masin, R., Zuin, M.C., Otto, S., Zanin, G., 2006. Seed longevity and dormancy of four summer annual grass weeds in turf. Weed Research, 46:362–370.

Mickelson, J.A., Harvey, R.G., 1999. Effects of *Eriochloa villosa* density and time of emergence on growth and seed production in *Zea mays*. Weed Science, 47:687-692.

Milton, S.J., 2004. Grasses as invasive alien plants in South Africa. South African Journal of Science, 100:69-75.

Mitich, L.W., 1988. Intriguing world of weeds. Crabgrasses. Weed Technology, 2:114-115.

Mohler, C.L., Calloway, M.B., 1992. Effects of tillage and mulch on the emergence and survival of weeds in sweet corn. Journal of Applied Ecology, 29:21-34.

Monaco, T.J., Weller, C.W., Ashton, F.M., 2002. 4th Edition. Weed Science: Principles and practices. John Wiley and Sons, Inc., New York. 671 p.

Monks, D.W., Schultheis, J.R., 1998, Critical weed-free period for large crabgrass (*Digitaria sanguinalis*) in transplanted watermelon (*Citrullus lanatus*). Weed Science, 46:530-532.

Mortimer, A.M., 1991. A review of graminicide resistance. Monograph No 1. HRAC - Graminicide Working Group. 28 p.

Myers, M.W., Curran, W.S., Vangessel, M.J., Calvin, D.D., Mortensen, D.A., Majek, B.A., Karsten, H.D., Roth, G.W., 2004. Predicting weed emergence for eight annual species in the Northern United States. Weed Science, 52:913-919.

Myers, M.W., Curran, W.S., Vangessel, M.J., Majek, B.A., Scott, B.A., Mortensen, D.A., Calvin, D.D., Karsten, H.D., Roth, G.W., 2005. The effect of weed density and application timing on weed control and corn grain yield. Weed Technology, 19:102-107.

Ngouajio, M., Lemieux, C., Leroux, P.F.D., 1999. Prediction of corn (*Zea mays*) yield loss from early observations of the relative leaf area and the relative leaf cover of weeds. Weed Science, 47:297-304.

Nishimoto, R.K., McCarty, L.B., 1997. Fluctuating temperature and light influence seed germination of goosegrass (*Eleusine indica*). Weed Science, 45:426-429.

Norsworthy, J.K., 2008. Effect of tillage intensity and herbicide programs on changes in weed species density and composition in the southern coastal plains of the United States. Crop Protection, 27:151-160.

Norsworthy, J.K., Meehan, J.T., 2005. Herbicidal activity of eight isothiocyanates on Texas panicum, *(Panicum texanum)*, large crabgrass (*Digitaria sanguinalis*), and sicklepod (*Sennaobtusifolia*). Weed Science, 53:515-520.

Norsworthy, J.K., Oliveira, M.J., 2004. Comparison of the critical period for weed control in wide-and narrow corn. Weed Science, 52:802-807.

Novak, M.G., Higley, L.G., Chrsitiansses, C.A., Rowling, W.A., 1993. Evaluating larval competition between *Aedes albopictus* and *A. triseriatus* (Diptera: Culcidae) through replacement series experiments. Environmental Entomology, 22:311-318.

Oksanen, L., Sammul, M., Mägi, M., 2006. On the indices of plant-plant competition and their pitfalls. Oikos, 112: 149-155.

Owen, M.D.K., Hartzler, R.G., Lux, J., 1993. Woolly cupgrass (*Eriochloa villosa*) control in corn (*Zea mays*) with chloroacetamide herbicides. Weed Technology, 7:925-929.

Page, E.R., Tollenaar, M., Lee, E.A., Lukens, L., Swanton, C.J., 2009. Does the shade avoidance response contribute to the critical period of weed control in corn (*Zea mays*)? Weed Research, 49:563-571.

Parker, R.G., York, A.C., Jordan, D.L., 2004. Evaluation of herbicide programmes in no- till and conventional tillage corn. 26th Sourthern Conservation Tillage Conference pp. 312-317.

Payne, R.W, ed., 2011. The guide to Genstat ®. Release 14, Part 2: Statistics VSN International, UK.

Pierce, G.L., Warren, S.L., Mikkelsen, R.L., Linker, H.M., 1999. Effects of soil calcium and pH on seed germination and subsequent growth of large crabgrass (*Digitaria sanguinalis*). Weed Technology, 13:421-424.

Radosevich, S.R., Holt, J.S., Ghersa, C.M., 1996. Weed ecology. 2nd Edition. Implications for management. John Wiley and Sons, Inc., New York. 589 p.

Radosevich, S.R., 1987. Methods to study interactions among crops and weeds. Weed Technology, 1:190-198.

Rajcan, I., Swanton, C.J., 2001. Understanding maize-weed competition: resources competition, light quality and the whole plant. Field Crops Research, 71:139:150.

Rajcan, I., Tollenaar, M. 1999. Source:sink ratio and leaf senescence in maize: I Dry matter accumulation and partitioning during grain filling. Field Crops Research 60: 245-253.

Rao, V.S., 2000. Principles of weed science. 2nd Edition. Sciences Publishers, Inc., Enfield (NH), USA. 555 p.

Richardson, D.M., Bond, W.J., Dean, W.J.R., Higgins, S.I., Midgley, G.F., Milton, S.J., Powrie, L.W., Rutherford, M.C., Samways, M.J., Schulze, R.E., 2000. Invasive alien organisms and global change: a South African perspective. In: Invasive species in a changing world, eds HA Mooney and RJ Hobbs, pp. 303-349, Island Press, Washington DC.

Richmond, D.S., Grewal, P.S., Cardina, J., 2003. Competition between *Lolium perenne* and *Digitaria sanguinalis*: Ecological consequences for harbouring an endosymbiotic fungus. Journal of Vegetative Science, 14:835-840.

Ritchie, S.W., Hanway, J.J., Benson, G.O., Herman, J.C., 2003. How a corn plant develops. Special Report No. 48. Ames, IA: Iowa State University of Science and Technology, Cooperative Extension Service.

Rouchard, J., Neus, O., Eelen, H., Bulcke, R., 2000. Dissipation and mobility of the herbicide mesotrione in the soil of corn crops. Mededelingen – Faculteit Landbouwkundige en Toegepaste Biologische Wetenschappen, Universiteit Gent, 65:51-58.

Saayman-Du Toit A.E.J., 2002. Phytotoxicity resulting from a combination of a PRE herbicide and a pesticide seed dressing in maize (*Zea mays* L.). South Africa Journal of Plant and Soil, 19:156-158.

Saayman-Du Toit, A.E.J., Le Court De Billot, M.R., 1991. Emergence patterns of certain weeds under field conditions. *Patrone van opkoms van sekere onkruide in veldtoestande*. South African Journal of Plant and Soil, 8:153-157

Sadeghi, A.M., Starr, J.L., Teasdale, J.R., Rosecrance, R.C., Rowland, R.A., 2007. Real-time soil profile water content as influenced by weed-corn competition. Soil Science, 172:759-769.

South African Grain Laboratory (SAGL), 2013. South African maize crop. Quality report 2012/2013 season. Pretoria, South Africa (http://www.sagl.co.za)

Sanydon, R.W., 1991. Replacement or additive designs for competition studies? Journal of Applied Ecology, 28:930-946.

SAS Institute, Inc., 1999. SAS/STAT User's Guide, Version 9, 1st printing, Volume 2. SAS Institute Inc, SAS Campus Drive, Cary, North Carolina 27513.

Scott-Craig, J.S., Casida, J.E., Poduje, L., Walton, J.D., 1998. Herbicide safener-binding protein of maize: Purification, cloning and expression of an encoding   cDNA.   Plant Physioliology, 116:1083-1089.

Shapiro, S.S., Wilk, M.B. 1965. Analysis of variance test for normality (complete samples). Biometrika, 52: 591-611.

Singh, M., Saxena, M.C., Abu-Irmaileh, B.E., Al-Thahabi, S.A., Haddad, N.I., 1996. Estimation of critical period of weed control. Weed Science, 44:273-283.

161

Smitchger, J.A., Burke, I.C., Yenish, J.P., 2012. The critical period of weed control in lentil (*Lens culinaris*) in the Pacific Northwest. Weed Science, 60:81-85.

Smith, R.G., 2006. Timing of tillage is an important filter on the assembly of weed communities. Weed Science, 54:705-712.

Snaydon, R.W. 1991. Replacement or additive designs for competition studies? Journal of Applied Ecology, 28:930-946.

Sosnoskie, L.M., Herms, C.P., Cardina, J., 2006. Weed seedbank community composition in a 35-yr-old tillage and rotation experiment. Weed Science, 54:263-273.

Souza, R.C.,Dias, A.C., Figueiredo, M.R.A., Obara, F.E.B., Christoffoleti, P.J., 2012. Growth of the crabgrass species *Digitaria ciliaris* and *Digitaria nuda*. Planta Daninha, 30:317-325.

Steinmaus, S. J., Prather, T.S., Holt, J.S., 2000. Estimation of base temperatures for nine weed species. Journal of Experimental Botany, 51:275-286.

Strahan, R.E., Griffin, J.L., Reynolds, D.B., Miller, D.K., 2000. Interference between *Rottboellia cochinchinensis* and *Zea mays*. Weed Science, 48:205-211.

Swanton, C.J., Weaver, S., Cowan, P., Van Acker, R., Deen, W., Shrestha, A. 1999. Weed thresholds: theory and applicability. Journal of Crop Production 2: 9-29.

Systat. 2002. Automated curve fitting and equation discovery. www.systat.com

Tapia, L.S., Bauman, T.T., Harvey, R.G., Kelly, J.J., Kapusta, G., Loux, M.M., Lueschen, W.M., Owen, M.D.K., Hageman, L.H., Strachan, S.D., 1997. POST herbicide application timing effects on annual grass control and corn (*Zea mays*) grain yield. Weed Science, 45:138-143.

Teuton, T.C., Brecke, B.J., Unruh, J.B., MacDonald, G.E., Miller, C.L., Ducar, J.T., 2004. Factors affecting seed germination of tropical signalgrass (*Urochloa subquadripara*). Weed Science, 52:376–381.

Tollenaar, M., Nissanka, S.P., Aguilera, A., Weise, S.F., Swanton, C.J., 1994. Effect of weed interference and soil nitrogen on four maize hybrids. Agronomy Journal, 86:596-601.

Tollenaar, M., 1992. Is low plant density a stress in maize? Maydica, 37:305-311.

162

Tollenaar, M., Aguilera, A., Nissanka, S.P., 1997. Grain yield is reduced more by weed interference in an old than in a new maize hybrid. Agronomy Journal, 89:239-246.

Tollenaar, M., Wu, J., 1999. Yield improvement in temperate maize is attributable to greater stress tolerance. Crop Science, 39:1597-1604.

Van Oudtshoorn, F., ed., 2009. Guide to grasses of southern Africa. 2nd ed., fifth impression. Briza Publications, Pretoria, South Africa. 288 p.

Vasilakoglou, I.B., Eleftherohorinos, I.G., Dhima, K.B., 2001. Activity, adsorption and mobility of three acetanilide and two amide herbicides. Weed Research, 41:535-546.

Vieira, V.C., Alves, P.L.D.A., Picchi, S.C., Lemos, M.V.F., Sena, J.A.D., 2010. Molecular characterization of accessions of crabgrass (*Digitaria nuda*) and respone to ametryn. Acta Scientiarum, Agronomy. Maringà 32, 255-261.

Wang, Q., Yang, W., Liu, W., 1999. Adsorption of acetanilide herbicides on soil and its correlation with soil properties. Pesticide Science, 55:1103-1108.

Webster, R.D., 1983. A revision of the genus *Digitaria* Haller (Paniceae: Poaceae) in Australia. Brunonia, 6: 131-216.

Weigelt, A., Jolliffe, P., 2003. Indices of plant competition. Journal of Ecology, 91: 707-720.

Wells, M.J., Harding, G.B., Balsinhas, A., Van Gass, B., 1980. A preliminary experiment in sampling agronomic weeds for a national survey. Proceedings of the third National weeds conference of South Africa. Eds. S Nesser and ALP Cairns. Cape Town A.A. Balkema Rotterdam.

Werner, H., 2002. Measuring soil moisture for irrigation water management. http://agbiopubs.sdstate.edu/articles/FS876.pdf

Wiederholdt, R.J., Stoltenberg, D.E., 1995. Cross-resistance of a large crabgrass (*Digitaria sanguinalis*) accession to aryloxyphenoxypropionate and cyclohexanedione herbicides. Weed Technology, 9:518-524.

Wiederholdt, R.J., Stoltenberg, D.E., 1996. Similar fitness between large crabgrass (*Digitaria sanguinalis*) accessions resistant or susceptible to acetyl-coenzyme A carboxylase inhibitors. Weed Technology, 10:42-49.

Williams, M.M., 2006. Planting date influences critical period of weed control in sweet corn. Weed Sciience, 54:928-933.

Wilson, J.B., 1988. Shoot and root competition. Journal of Applied Ecology, 25: 279-296.

Xu, B-C.,Xu, W-Z., Huan, J., Shan, L. Li, F-M., 2011. Biomass allocation, relative competitive ability and water use efficiency of two dominant species in semiarid Loess Plateau under water stress. Plant Science, 181: 644-651.

Young, F.L., Wyse, D.L., Jones, R.J., 1984. Quackgrass (*Agropyron repens*) interference on corn (*Zea mays*). Weed Science, 32:226-234.

Zimdahl, R.L., 2004. Weed-Crop competition: A review. Blackwell Publishing Ltd., Oxford, 220 p.

Zhou, B., Kong, C-H., Li, Y-H, Wang, P., Xu, X-H., 2013. Crabgrass (*Digitaria sanguinalis*) allelochemicals that interfere with crop growth and the soil microbial community. Journal of Agricultural Food Chemistry, 61:5310-5317.

APPENDIX A: LABORATORY ANALYSIS

Table A.1. Soil analysis* of two soil types used in glasshouse trials to determine competition effect of naked crabgrass and large crabgrass on maize (Chapter 4)

Soil type	N-NO3	N-NH4	P(Bray1)	K	Ca	Mg	Na	Fe	Cu	Zn	Mn	pH (KCl)	Clay	Sand	Silt
	mg.kg-1													%	
Sandy clay-loam soil	11.65	0.5	51	48	420	160	25	23	0.6	15	16	8.12	36	59	5
Sandy loam soil	14.4	3.6	28	255	1150	453	15	4.52	1.96	5.32	29	6.41	16	79	5

*Soil analysis was done by the ARC-Institute for Soil, climate and water

Table A.2. Soil analysis* of two loacalities where field trials were conducted to determine the critical period of weed control of naked crabgrass (Chapter 5)

Locality	N-NO3	N-NH4	P	K	Ca	Mg	Na	pH (KCl)	Clay	Sand	Silt
	mg/kg									%	
Potchefstroom (sandy clay-loam)	3.21	9.6	59.2	245	922	362	17.4	6.58	36	59	5
Wesselsbron (sandy)	3.96	9.4	38.2	155	293	101	0.88	6.73	10	84	6

*Soil analysis was done by the ARC-Institute for Soil, climate and water

Table A.3. Leaf analysis* of maize in competition trials with naked crabgrass on clay and sandy soils. [Chapter 4]

Soil type	Treatment ratio	Leave stage	N %	P %	K %	Ca %	Mg %	Na mg/kg	Mn mg/kg	Fe mg/kg	Cu mg/kg	Zn mg/kg	B mg/kg	Mo mg/kg	S %
Sandy	1:0	Seedling	4.63	0.32	5.95	0.76	0.87	155	30	114	9	77	11	0.31	0.30
	1:2		4.52	0.34	4.21	0.88	1.29	132	24	118	10	84	11	0.57	0.31
	1:3		3.91	0.36	3.69	0.84	1.25	120	27	116	10	75	10	0.55	0.33
	1:4		3.79	0.33	3.72	0.89	1.27	121	26	113	9	72	9	0.62	0.27
	1:5		3.74	0.36	3.82	0.85	1.30	146	25	109	9	71	9	0.39	0.35
	1:6		3.69	0.40	4.52	0.86	1.17	165	25	117	10	71	10	0.50	0.35
	1:0	Mature	1.96	0.33	1.98	0.65	0.67	157	23	138	13	40	41	0.40	0.35
	1:2		2.34	0.36	1.42	0.87	0.95	141	17	191	18	50	33	0.46	0.46
	1:3		2.56	0.34	1.65	0.69	0.72	138	39	282	11	33	35	0.23	0.33
	1:4		2.49	0.34	1.66	0.79	0.76	148	46	215	15	34	32	0.37	0.38
	1:5		2.47	0.32	1.36	0.83	0.90	148	20	199	14	34	37	0.57	0.40
	1:6		2.80	0.40	1.84	0.71	0.71	141	19	230	15	42	39	0.48	0.44
Clay	1:0	Seedling	2.94	0.41	2.24	0.49	0.40	105	42	159	8	43	41	0.15	0.37
	1:2		3.15	0.38	2.63	0.46	0.38	130	39	167	13	35	44	0.10	0.38
	1:3		3.18	0.33	2.60	0.41	0.38	93	36	143	13	34	35	0.05	0.32
	1:4		3.00	0.34	2.59	0.43	0.40	96	37	142	11	35	34	0.12	0.29
	1:5		3.24	0.36	2.75	0.46	0.41	97	37	160	12	36	31	0.06	0.36
	1:6		3.51	0.14	1.61	1.49	0.75	89	526	182	5	9	19	0.24	0.33
	1:0	Mature	3.23	0.17	5.58	0.66	0.44	100	39	218	9	32	8	<0.01	0.18
	1:2		3.41	0.18	5.68	0.62	0.45	123	37	191	10	32	7	0.01	0.19
	1:3		3.28	0.17	5.15	0.62	0.45	71	50	185	10	34	10	0.11	0.20
	1:4		3.25	0.19	5.75	0.68	0.48	145	40	190	10	37	7	0.04	0.21
	1:5		3.21	0.15	5.12	0.49	0.38	74	29	118	6	27	5	0.09	0.17
	1:6		3.21	0.17	5.26	0.64	0.43	104	51	215	9	31	9	0.11	0.22

*SGS laboratories, Somerset West, Reg No.: 96/17268/07)

166

Table A.4. Leaf analysis* of maize in competition trials with large crabgrass on clay and sandy soils. [Chapter 4]

Soil type	Treatment ratio	Leave stage	N %	P %	K %	Ca %	Mg %	Na mg/kg	Mn mg/kg	Fe mg/kg	Cu mg/kg	Zn mg/kg	B mg/kg	Mo mg/kg	S %
Sandy	1:0	Seedling	4.36	0.68	2.82	0.86	1.14	295	65	110	6	55	5	0.65	0.19
	1:2		4.37	0.72	3.01	0.73	1.10	268	72	110	6	53	6	1.09	0.19
	1:3		4.34	0.71	2.61	0.78	1.10	367	82	138	5	52	6	0.65	0.18
	1:4		4.32	0.69	2.79	0.90	1.22	242	77	114	6	49	6	0.91	0.18
	1:5		4.19	0.75	2.47	0.83	1.18	247	81	192	6	58	6	0.97	0.18
	1:6		4.62	0.86	2.77	0.80	1.10	234	79	111	6	51	6	0.74	0.20
	1:0	Mature	1.66	0.10	0.77	0.44	0.44	166	20	54	3	16	9	0.18	0.05
	1:2		1.03	0.14	1.18	0.71	0.72	363	93	95	4	30	22	0.90	0.07
	1:3		1.25	0.11	0.60	0.30	0.39	149	34	43	2	16	7	0.46	0.03
	1:4		1.07	0.16	1.29	0.47	0.71	183	39	82	3	24	10	0.60	0.07
	1:5		0.86	0.13	0.95	0.56	0.72	225	76	129	4	31	12	0.52	0.06
	1:6		1.17	0.16	1.03	0.54	0.81	183	72	76	3	27	10	0.82	0.07
Clay	1:0	Seedling	4.79	0.59	5.85	0.72	0.48	292	80	136	10	68	7	0.30	0.19
	1:2		4.86	0.57	5.98	0.81	0.50	215	84	153	12	69	7	0.73	0.20
	1:3		4.88	0.55	5.42	0.75	0.52	234	70	128	12	68	7	0.72	0.19
	1:4		4.86	0.60	5.41	0.88	0.49	230	97	149	11	71	7	0.93	0.21
	1:5		4.55	0.49	5.56	0.72	0.46	232	68	112	11	67	6	0.65	0.17
	1:6		4.76	0.61	5.80	0.76	0.47	303	82	139	12	75	7	0.56	0.20
	1:0	Mature	1.67	0.14	1.70	0.62	0.25	180	51	114	2	28	19	0.26	0.08
	1:2		1.22	0.12	2.26	0.41	0.19	183	34	89	3	25	19	0.24	0.05
	1:3		1.36	0.24	2.16	0.51	0.19	674	41	99	4	27	17	1.01	0.23
	1:4		1.37	0.15	2.16	0.41	0.18	239	46	110	3	28	16	0.32	0.06
	1:5		1.32	0.16	2.20	0.44	0.24	209	63	84	4	31	19	0.09	0.06
	1:6		1.27	0.13	1.85	0.37	0.20	198	36	76	3	25	18	0.62	0.06

*SGS laboratories, Somerset West, Reg No.: 96/17268/07)

APPENDIX B: TRIAL PHOTOS [Glasshouse and field trials conducted for this study]
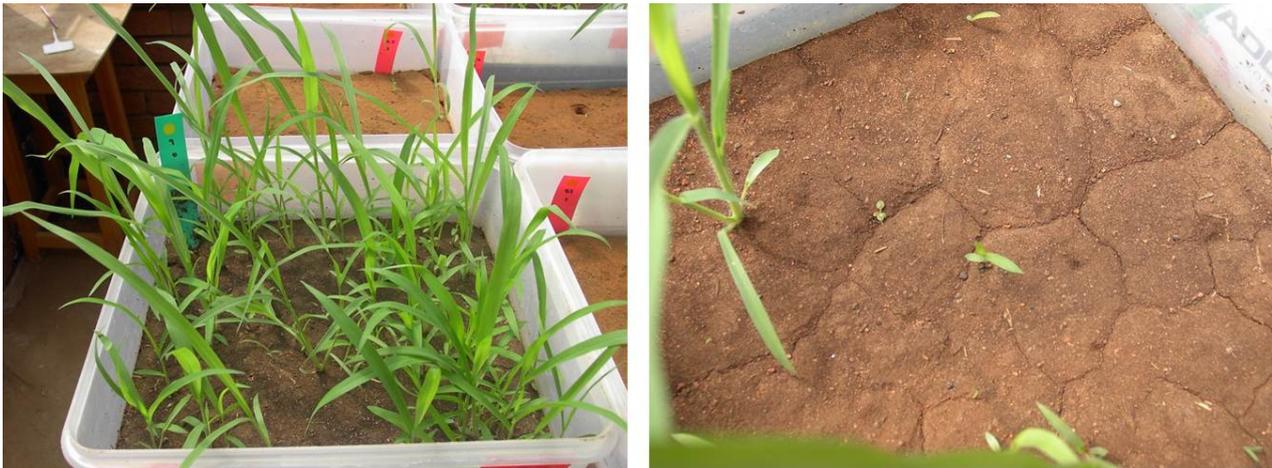
Photo B1: (Chapter 2) Emergence of naked crabgrass at different burial depths, done on two soil types in a greenhouse.
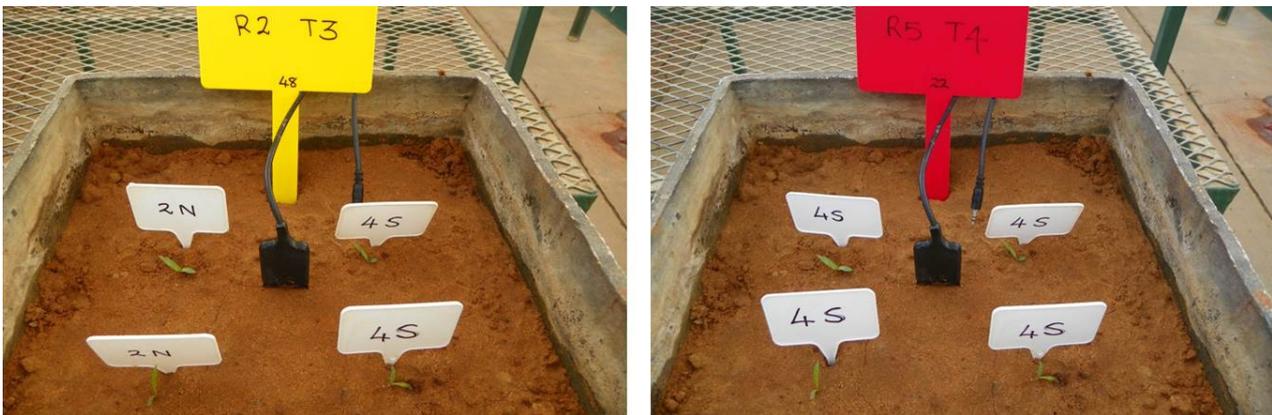
Photo B2: (Chapter 3) Arrangement of naked crabgrass and large crabgrass seedlings in the replacement series design, tested in a wet and dry soil profile.

168

Photo B3: (Chapter 4) Competition trials of naked crabgrass and large crabgrass with maize, done on two soil types in a greenhouse (seedling stage and mature plants).

Photo B4: (Chapter 3) Competition trial with naked crabgrass and maize (grown to maturity) and the measurement of soil water content with a Decagon ECHO Check handheld meter.

Photo B5: (Chapter 6) Application of herbicides and rectangular conatiners in which naked crabgrass and large crabgrass was planted prior to application of PRE herbicides (left, control treatment visible on photo).

Photo B6: (Chapter 6) Field trial 1. Infestation levels of naked crabgrass in the different herbicide treatments (2 = s-metolachlor, 3 = acetochlor, 4 = mesotrione, 10 = control).

Photo B7 (Chapter 6) Field trial 2. Infestation levels and trial layout to evaluate control of nine herbicide programmes on maize.

APPENDIX C: STATISTICAL ANALYSIS

Chapter 2 (Germination chracteristics)

Table C2.1. Mitscherlich analysis of cumulative germination of naked crabgrass at different temperature regimes and pre-treatments of stored and fresh seed. [Growth chamber trial: Figure 2.1]

		Stored seed: Control				Fresh seed: Control			
		10/25 C				10/25 C			
Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Model	2	198.60	99.30	7.29	0.0705	321.40	160.71	625.39	<.0001
Residual	4	40.87	13.62			0.40	0.10		
Total	6	239.50				321.80			
Parameter	Estimate	SE				Estimate	SE		
M	14.88	3.39				19.95	0.17		
K	0.17	0.12				0.37	0.02		
L	4.60	1.11				0.00	0.04		
		15/30 C				15/30 C			
Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Model	2	3626.70	1813.30	11.9	0.0207	164.10	82.04	21.86	0.007
Residual	4	609.30	152.30			15.01	3.75		
Total	6	4236.00				179.10			
Parameter	Estimate	SE				Estimate	SE		
M	68.99	17.55				28.76	32.46		
K	0.10	0.06				0.02	0.04		
L	0.74	1.47				2.01	1.81		
		25 C				25 C			
Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Model	2	1125.00	562.50	209.94	<.0001	2881.80	1440.90	79.93	0.0006
Residual	4	10.72	2.68			72.11	18.03		
Total	6	1135.70				2953.90			
Parameter	Estimate	SE				Estimate	SE		
M	37.24	0.83				67.06	7.73		
K	0.43	0.07				0.08	0.02		
L	-0.01	0.10				0.31	0.68		
		30 C				30 C			
Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Model	2	889.10	444.60	526.79	<.0001	184.80	92.41	4704.7	<.0001
Residual	4	1.16	0.29			0.01	0.00		
Total	6	890.30				184.80			
Parameter	Estimate	SE				Estimate	SE		
M	32.70	0.26				14.83	0.02		
K	0.59	0.05				0.69	0.02		
L	0.00	0.03				0.00	0.01		

		Stored seed: KNO$_3$ pre-treatment				Fresh seed: KNO$_3$ pre-treatment			
		10/25 C					**10/25 C**		
Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Model	2	96.74	48.37	90.26	<.0001	186.50	93.26	33.54	0.0032
Residual	4	0.18	0.04			11.12	2.78		
Total	6	96.92				197.60			

Parameter	**Estimate**	**SE**				**Estimate**	**SE**		
M	10.77	0.10				15.56	1.45		
K	0.61	0.06				0.15	0.05		
L	0.00	0.03				0.11	0.68		

		15/30 C					**15/30 C**		
Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Model	2	204.80	102.40	237.5	<.0001	2001.00	1000.50	213.62	<.0001
Residual	4	1.72	0.43			18.73	4.68		
Total	6	206.50				2019.70			

Parameter	**Estimate**	**SE**				**Estimate**	**SE**		
M	15.78	0.32				51.63	1.64		
K	0.51	0.09				0.17	0.02		
L	0.00	0.08				-0.06	0.24		

		25 C					**25 C**		
Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Model	2	8974.20	4487.10	36.22	0.0027	1265.40	632.70	39.97	0.0023
Residual	4	495.50	123.90			63.31	15.83		
Total	6	9469.70				1328.70			

Parameter	**Estimate**	**SE**				**Estimate**	**SE**		
M	104.40	6.86				39.26	2.48		
K	0.24	0.07				0.24	0.07		
L	0.09	0.42				0.09	0.40		

		30 C					**30 C**		
Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Model	2	6514.20	3257.10	35.67	0.0028	501.50	250.80	27.53	0.0046
Residual	4	365.30	91.32			36.44	9.11		
Total	6	6879.50				537.90			

Parameter	**Estimate**	**SE**				**Estimate**	**SE**		
M	88.90	5.90				24.57	1.92		
K	0.24	0.07				0.23	0.07		
L	0.09	0.42				0.13	0.50		

		Stored seed: Imbibition with water 24 h				Fresh seed: Imbibition with water 24 h			
		10/25 C					**10/25 C**		
Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Model	2	384.00	192.00	27.57	0.0046	49.04	24.52	7.32	0.046
Residual	4	27.86	6.97			13.40	3.35		
Total	6	411.90				62.44			

Parameter	**Estimate**	**SE**				**Estimate**	**SE**		
M	63.66	107.50				8.00	3.50		
K	0.02	0.03				0.08	0.07		
L	1.08	2.00				1.59	1.96		

		15/30 C				15/30 C			
Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Model	2	9301.30	4650.60	14.18	0.0153	3323.50	1661.70	21.35	0.0073
Residual	4	1311.70	327.90			311.30	77.83		
Total	6	10613.00				3634.80			

Parameter	Estimate	SE				Estimate	SE		
M	104.10	19.64				70.87	20.09		
K	0.12	0.06				0.07	0.04		
L	0.79	1.14							

		25 C				25 C			
Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Model	2	2206.90	1103.40	36.12	0.0028	7776.30	3888.20	35.2	0.0029
Residual	4	122.20	30.55			441.90	110.50		
Total	6	2329.10				8218.20			

Parameter	Estimate	SE				Estimate	SE		
M	51.69	3.66				97.12	6.50		
K	0.21	0.06				0.24	0.07		
L	0.13	0.47				0.10	0.42		

		30 C				30 C			
Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Model	2	5067.00	2533.50	30.22	0.0039	8683.80	4341.90	38.19	0.0025
Residual	4	335.30	83.83			454.80	113.70		
Total	6	5402.40				9138.50			

Parameter	Estimate	SE				Estimate	SE		
M	78.23	5.76				102.70	6.53		
K	0.23	0.07				0.25	0.07		
L	0.11	0.47				0.09	0.40		

Table C2.2. ANOVA table of maximum germination (%) where one-year old and fresh naked crabgrass seed were pre-treated with different treatments and germinated at different temperature regimes. [Growth chamber trial: Table 2.4]

Maximum germination (%)					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
TEMP.REP stratum					
TEMPERATURE (TEMP)	3	34838.1	11612.7	46.9	<.001
Residual	12	2971	247.6	1.58	
TEMP.REP.TMT.SEED stratum					
TREATMENT (TMT)	4	28396.3	7099.1	45.41	<.001
SEED (AGE)	1	9860.2	9860.2	63.08	<.001
TEMP.TMT	12	24672.2	2056	13.15	<.001
TEMP.SEED	3	4819.5	1606.5	10.28	<.001
TMT.SEED	4	6216.6	1554.1	9.94	<.001
TEMP.TMT.SEED	12	24826.2	2068.9	13.24	<.001
Residual	106	16569.5	156.3		
Total	157	149570.8			

	Temperature	Treatment	Seed age	Temperature Treatment	Temperature Seed age	Treatment Seed age	Temperature Treatment Seed age
LSD(0.05)	7.67	6.18	3.92	13.13	9.17	8.76	18.02
SEM	2.49	2.21	1.39	4.67	3.18	3.13	6.43
CV (%)	33.3						

Table C2.3. ANOVA table for maximum germination of one year old and fresh naked crabgrass seed, pre-chilled for 3 months in different pre-treatments. [Growth chamber trial: Figure 2.2]

Maximum germination (%)					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
PRECHILL	1	9234.3	9234.3	57.74	<.001
SEED (AGE)	1	14589.9	14589.9	91.22	<.001
TREATMENTS (TMT)	4	15444	3861	24.14	<.001
PRECHILL.SEED	1	18.6	18.6	0.12	0.734
PRECHILL.TMT	4	5460.7	1365.2	8.54	<.001
SEED.TMT	4	9405.7	2351.4	14.7	<.001
PRECHILL.SEED.TMT	4	9796.5	2449.1	15.31	<.001
Residual	59	9436.6	159.9		
Total	78	72797.7			

	Pre-chill	Seed	Treatment	Pre-chill Seed age	Pre-chill Treatment	Seed age Treatment	Pre-chill Seed age Treatment
LSD(0.05)	5.66	5.66	8.95	8	12.65	12.65	17.89
SEM	2.0	2.0	3.16	2.83	4.47	4.47	6.32
CV (%)	23.8						

175

Table C2.4. ANOVA table of mean time to emergence and dry mass of naked crabgrass seedlings emerged in two soil types at different burial depths. [Glasshouse trial: figure 2.3]

Mean germination time (days)					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
REP stratum	3	1184.62	394.87	18.97	
REP.*Units* stratum					
SOIL (clay %)	1	57.27	57.27	2.75	0.099
DEPTH (Burial depth)	7	742.41	106.06	5.1	<.001
SEED (Year)	2	47.37	23.69	1.14	0.323
SOIL.DEPTH	7	40.89	5.84	0.28	0.961
SOIL.SEED	2	28.88	14.44	0.69	0.501
DEPTH.SEED	14	254.27	18.16	0.87	0.59
SOIL.DEPTH.SEED	14	218.09	15.58	0.75	0.722
Residual	141	2934.35	20.81		
Total	191	5508.16			

	Soil	Depth	Seed year	Soil. Depth	Soil Seed	Depth. Seed	Soil. Depth Seed
LSD (P=0.05)	0.912	2.45	1.12	2.58	1.57	3.16	4.47
SEM	0.466	0.931	0.57	1.317	0.806	1.613	2.281
CV (%)	40						

Dry mass (g.plant-1)					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
REP stratum	5	2048.41	409.68	38.79	
REP.*Units* stratum					
SOIL (clay %)	1	318.83	318.83	30.19	<.001
DEPTH (Burial depth)	7	1151.31	164.47	15.57	<.001
SEED (Year)	2	25.62	12.81	1.21	0.299
SOIL.DEPTH	7	87.93	12.56	1.19	0.309
SOIL.SEED	2	2.05	1.03	0.1	0.907
DEPTH.SEED	14	128.39	9.17	0.87	0.594
SOIL.DEPTH.SEED	14	54.76	3.91	0.37	0.982
Residual	235	2481.69	10.56		
Total	287	6299			

	Soil	Depth	Seed year	Soil. Depth	Soil Seed	Depth. Seed	Soil. Depth. Seed
LSD (P=0.05)	0.531	1.5	0.65	1.06	0.919	1.84	2.6
SEM	0.271	0.542	0.332	0.766	0.469	0.938	1.327
CV (%)	82.3						

176

Table C2.5. Regression analysis for total plants emerged where naked crabgrass seed, sampled in different years, was planted in two soil types at different burial depths. [Glasshouse trial: Figure 2.4]

Total plants emerged for seed year 2007

Soil 16 % clay

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	3232.2	1616.12	35.02	<.001
Residual	6	276.9	46.15		
Total	8	3509.2	438.64		
Variance (%)	71.8				
R^2	75.8				
SE	6.79				

Soil 36 % clay

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	5663.4	2831.69	34.76	<.001
Residual	6	488.7	81.45		
Total	8	6152.1	769.01		
Variance (%)	53.3				
R^2	60.00				
SE	9.03				

Total plants emerged for seed year 2008

Soil 16 % clay

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	11725.7	5862.83	65.25	<.001
Residual	6	539.1	89.85		
Total	8	12264.7	1533.09		
Variance (%)	84.5				
R^2	86.7				
SE	9.48				

Soil 36 % clay

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	21863	10931.48	140.53	<.001
Residual	6	466.7	77.79		
Total	8	22329.7	2791.21		
Variance (%)	90.3				
R^2	91.7				
SE	8.82				

Total Plants emerged for seed year 2010

Soil 16 % clay

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	12185	6092.5	57.01	<.001
Residual	6	641.3	106.9		
Total	8	12826.2	1603.3		
Variance (%)	76.3				
R^2	79.7				
SE	10.3				

Soil 36 % clay

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	12939.5	6469.77	186.07	<.001
Residual	6	208.6	34.77		
Total	8	13148.2	1643.52		
Variance (%)	92.9				
R^2	93.9				
SE	5.9				

Chapter 3 (Competitive ability)

Table C3.1. ANOVA table for biomass parameters as influenced by competitive ability of both naked crabgrass and large crabgrass in a replacement series trial. [Glasshouse trial: Figures 3.1 and 3.2; Tables 3.1 and 3.2]

Panicle mass (g.pot-1)

Source	d.f.	s.s	m.s.	v.r.	F pr.
REP	7	14.28	2.04	0.4	0.8766
Soil profile (SOIL)	1	20.57	20.57	4.01	0.0853
SOIL*REP	7	35.90	5.13		
Treatment combinations (RATIO)	4	71.22	17.81	14.18	<.0001
RATIO*SOIL	4	3.20	0.80	0.64	0.6368
Grasses (SPECIES)	1	4.25	4.25	3.38	0.0689
SOIL*SPECIES	1	0.09	0.09	0.07	0.7941
RATIO*SPECIES	2	126.07	63.04	50.19	<.0001
RATIO*SOIL*SPECIES	2	7.82	3.91	3.11	0.049
Residual	96	120.56	1.26		
Total	125	403.96			

	SOIL	RATIO	SPECIES	RATIO. SOIL	SOIL. SPECIES	RATIO. SPECIES	RATIO. SOIL. SPECIES
LSD (P = 0.05)	0.954	0.666	0.396	0.942	0.561	0.793	1.122
CV (%)	39.53						

Seed mass (g.pot-1)

Source	d.f.	s.s	m.s.	v.r.	F pr.
REP	7	31.77	4.54	0.64	0.7161
Soil profile (SOIL)	1	29.23	29.23	4.11	0.0823
SOIL*REP	7	49.79	7.11		
Treatment combinations (RATIO)	4	44.47	11.12	3.46	0.011
RATIO*SOIL	4	9.90	2.48	0.77	0.5468
Grasses (SPECIES)	1	54.59	54.59	17	<.0001
SOIL*SPECIES	1	0.19	0.19	0.06	0.8081
RATIO*SPECIES	2	85.67	42.83	13.34	<.0001
RATIO*SOIL*SPECIES	2	14.09	7.04	2.19	0.1172
Residual	96	308.35	3.21		
Total	125	628.04			

	SOIL	RATIO	SPECIES	RATIO. SOIL	SOIL. SPECIES	RATIO. SPECIES	RATIO. SOIL. SPECIES
LSD (P = 0.05)	1.124	1.065	0.634	1.507	0.896	1.268	1.795
CV (%)	86.25						

Tiller mass (g.pot-1)

Source	d.f.	s.s	m.s.	v.r.	F pr.
REP	7	460.23	65.75	0.62	0.728
Soil profile (SOIL)	1	371.65	371.65	3.51	0.1033
SOIL*REP	7	741.87	105.98		
Treatment combinations (RATIO)	4	2283.74	570.93	20.15	<.0001
RATIO*SOIL	4	197.98	49.50	1.75	0.146
Grasses (SPECIES)	1	45.12	45.12	1.59	0.2101
SOIL*SPECIES	1	1.97	1.97	0.07	0.7928
RATIO*SPECIES	2	3169.79	1584.90	55.94	<.0001
RATIO*SOIL*SPECIES	2	162.90	81.45	2.87	0.0613
Residual	96	2720.11	28.33		
Total	125	10155.35			

	SOIL	RATIO	SPECIES	RATIO. SOIL	SOIL. SPECIES	RATIO. SPECIES	RATIO. SOIL. SPECIES
LSD (P = 0.05)	4.338	3.162	1.883	4.475	2.663	3.767	5.33
CV (%)	36.6						

178

Shoot mass (g.pot-1)

Source	d.f.	s.s	m.s.	v.r.	F pr.
REP	7	673.00	96.14	0.54	0.7822
Soil profile (SOIL)	1	483.21	483.21	2.72	0.1433
SOIL*REP	7	1245.32	177.90		
Treatment combinations (RATIO)	4	2934.99	733.75	17.04	<.0001
RATIO*SOIL	4	216.37	54.09	1.26	0.2927
Grasses (SPECIES)	1	45.78	45.78	1.06	0.3051
SOIL*SPECIES	1	0.15	0.15	0	0.9529
RATIO*SPECIES	2	4938.24	2469.12	57.34	<.0001
RATIO*SOIL*SPECIES	2	169.80	84.90	1.97	0.1448
Residual	96	4133.80	43.06		
Total	125	14840.66			

	SOIL	RATIO	SPECIES	RATIO. SOIL	SOIL. SPECIES	RATIO. SPECIES	RATIO. SOIL. SPECIES
LSD (P = 0.05)	5.62	3.898	2.321	5.517	3.283	4.643	6.571
CV (%)	37.41						

Root mass (g.pot-1)

Source	d.f.	s.s	m.s.	v.r.	F pr.
REP	7	40.21	5.74	1.04	0.4792
Soil profile (SOIL)	1	21.83	21.83	3.96	0.0869
SOIL*REP	7	38.60	5.51		
Treatment combinations (RATIO)	4	207.80	51.95	15.88	<.0001
RATIO*SOIL	4	18.13	4.53	1.39	0.2446
Grasses (SPECIES)	1	0.49	0.49	0.15	0.701
SOIL*SPECIES	1	0.05	0.05	0.01	0.903
RATIO*SPECIES	2	224.93	112.46	34.38	<.0001
RATIO*SOIL*SPECIES	2	3.62	1.81	0.55	0.5768
Residual	96	314.01	3.27		
Total	125	869.65			

	SOIL	RATIO	SPECIES	RATIO. SOIL	SOIL. SPECIES	RATIO. SPECIES	RATIO. SOIL. SPECIES
LSD (P = 0.05)	0.989	1.074	0.639	1.521	0.905	1.279	1.811
CV (%)	43.99						

Total biomass (g.pot-1)

Source	d.f.	s.s	m.s.	v.r.	F pr.
REP	7	653.89	93.41	0.43	0.8567
Soil profile (SOIL)	1	299.63	299.63	1.38	0.2792
SOIL*REP	7	1524.58	217.80		
Treatment combinations (RATIO)	4	4602.85	1150.71	20.86	<.0001
RATIO*SOIL	4	258.69	64.67	1.17	0.328
Grasses (SPECIES)	1	55.69	55.69	1.01	0.3176
SOIL*SPECIES	1	0.37	0.37	0.01	0.9348
RATIO*SPECIES	2	7268.36	3634.18	65.87	<.0001
RATIO*SOIL*SPECIES	2	149.82	74.91	1.36	0.2622
Residual	96	5296.90	55.18		
Total	125	20110.79			

	SOIL	RATIO	SPECIES	RATIO. SOIL	SOIL. SPECIES	RATIO. SPECIES	RATIO. SOIL. SPECIES
LSD (P = 0.05)	6.219	4.413	2.627	6.245	3.716	5.256	7.438
CV (%)	34.3						

179

Root:Shoot ratio

Source	d.f.	s.s	m.s.	v.r.	F pr.
REP	7	0.39	0.06	2.87	0.0091
Soil profile (SOIL)	1	0.26	0.26	13.53	0.0004
SOIL*REP	7	0.12	0.02		
Treatment combinations (RATIO)	4	0.06	0.01	0.73	0.5747
RATIO*SOIL	4	0.06	0.01	0.72	0.5779
Grasses (SPECIES)	1	0.02	0.02	1.21	0.274
SOIL*SPECIES	1	0.00	0.00	0.07	0.785
RATIO*SPECIES	2	0.01	0.00	0.2	0.8151
RATIO*SOIL*SPECIES	2	0.01	0.00	0.16	0.8493
Residual	96	1.87	0.02		
Total	125	2.80			

	SOIL	RATIO	SPECIES	RATIO. SOIL	SOIL. SPECIES	RATIO. SPECIES	RATIO. SOIL. SPECIES
LSD (P = 0.05)	0.055	0.083	0.049	0.117	0.069	0.098	0.139
CV (%)	52.44						

Number of panicles (per pot)

Source	d.f.	s.s	m.s.	v.r.	F pr.
REP	7	193.02	27.57	0.37	0.8917
Soil profile (SOIL)	1	2328.22	2328.22	31.49	0.0008
SOIL*REP	7	517.51	73.93		
Treatment combinations (RATIO)	4	1410.53	352.63	18.6	<.0001
RATIO*SOIL	4	1594.87	398.72	21.03	<.0001
Grasses (SPECIES)	1	119.34	119.34	6.29	0.0138
SOIL*SPECIES	1	435.04	435.04	22.94	<.0001
RATIO*SPECIES	2	1556.90	778.45	41.05	<.0001
RATIO*SOIL*SPECIES	2	493.17	246.59	13	<.0001
Residual	96	1820.38	18.96		
Total	125	10468.98			

	SOIL	RATIO	SPECIES	RATIO. SOIL	SOIL. SPECIES	RATIO. SPECIES	RATIO. SOIL. SPECIES
LSD (P = 0.05)	3.623	2.587	1.54	3.661	2.178	3.081	4.36
CV (%)	34.75						

Number of tillers (per pot)

Source	d.f.	s.s	m.s.	v.r.	F pr.
REP	7	247.35	35.34	0.43	0.8554
Soil profile (SOIL)	1	1747.34	1747.34	21.31	0.0024
SOIL*REP	7	574.01	82.00		
Treatment combinations (RATIO)	4	2263.74	565.93	30.91	<.0001
RATIO*SOIL	4	1630.14	407.54	22.26	<.0001
Grasses (SPECIES)	1	9.28	9.28	0.51	0.4783
SOIL*SPECIES	1	394.63	394.63	21.55	<.0001
RATIO*SPECIES	2	1795.59	897.79	49.03	<.0001
RATIO*SOIL*SPECIES	2	416.78	208.39	11.38	<.0001
Residual	96	1757.75	18.31		
Total	125	10836.61			

	SOIL	RATIO	SPECIES	RATIO. SOIL	SOIL. SPECIES	RATIO. SPECIES	RATIO. SOIL. SPECIES
LSD (P = 0.05)	3.816	2.542	1.513	3.597	2.141	3.028	4.285
CV (%)	30.17						

180

Table C3.2. ANOVA tables of competitive indices where naked crabgrass and large crabgrass was grown in a replacement series trial. [Glasshouse trial: Tables 3.4 and 3.5]

Competitive ratio (Shoot mass g.plant-1)					
Source	**d.f.**	**s.s**	**m.s.**	**v.r.**	**F pr.**
REP	7	1.146	0.164	0.4	0.8732
(Soil profile) SOIL	1	0.038	0.038	0.09	0.7698
SOIL*REP	7	2.844	0.406		
Treatment combinations (RATIO)	2	11.744	5.872	10.34	0.0001
RATIO*SOIL	2	1.990	0.995	1.75	0.1808
Grasses (SPECIES)	1	1.848	1.848	3.26	0.0755
SOIL*SPECIES	1	5.539	5.539	9.76	0.0026
RATIO*SPECIES	2	153.165	76.582	134.89	<.0001
RATIO*SOIL*SPECIES	2	0.410	0.205	0.36	0.6983
Residual	70	39.741	0.568		
Total	95	218.466			

	SOIL	RATIO	SPECIES	RATIO. SOIL	SOIL. SPECIES	RATIO. SPECIES	RATIO. SOIL. SPECIES
LSD (P = 0.05)	0.308	0.376	0.307	0.531	0.434	0.531	0.751
CV (%)	46.36						

Competitive ratio (Root mass g.plant-1)					
Source	**d.f.**	**s.s**	**m.s.**	**v.r.**	**F pr.**
REP	7	3.543	0.506	0.64	0.7152
(Soil profile) SOIL	1	0.549	0.549	0.69	0.4324
SOIL*REP	7	5.541	0.792		
Treatment combinations (RATIO)	2	11.004	5.502	7.16	0.0015
RATIO*SOIL	2	0.847	0.424	0.55	0.5787
Grasses (SPECIES)	1	1.302	1.302	1.69	0.1973
SOIL*SPECIES	1	4.744	4.744	6.17	0.0154
RATIO*SPECIES	2	139.351	69.676	90.69	<.0001
RATIO*SOIL*SPECIES	2	1.488	0.744	0.97	0.3846
Residual	70	53.781	0.768		
Total	95	222.150			

	SOIL	RATIO	SPECIES	RATIO. SOIL	SOIL. SPECIES	RATIO. SPECIES	RATIO. SOIL. SPECIES
LSD (P = 0.05)	0.429	0.437	0.357	0.618	0.505	0.618	0.874
CV (%)	55.38						

Competitive ration (Total biomass g.plant-1)					
Source	**d.f.**	**s.s**	**m.s.**	**v.r.**	**F pr.**
REP	7	1.878	0.268	1.58	0.2807
(Soil profile) SOIL	1	0.004	0.004	0.02	0.888
SOIL*REP	7	1.189	0.170		
Treatment combinations (RATIO)	2	12.094	6.047	13.94	<.0001
RATIO*SOIL	2	2.400	1.200	2.77	0.0697
Grasses (SPECIES)	1	0.092	0.092	0.21	0.6467
SOIL*SPECIES	1	6.526	6.526	15.05	0.0002
RATIO*SPECIES	2	164.049	82.024	189.12	<.0001
RATIO*SOIL*SPECIES	2	0.221	0.110	0.25	0.776
Residual	70	30.360	0.434		
Total	95	218.813			

	SOIL	RATIO	SPECIES	RATIO. SOIL	SOIL. SPECIES	RATIO. SPECIES	RATIO. SOIL. SPECIES
LSD (P = 0.05)	0.199	0.328	0.268	0.464	0.379	0.464	0.657
CV (%)	40.12						

Table C3.3. ANOVA tables of relative yield and relative yield total for naked crabgrass and large crabgrass in a replacement series experiment. [Glasshouse trial: Table 3.6]

		Digitaria nuda				*Digitaria sanguinalis*			
				Shoot mass (g.plant-1)					
Source	d.f.	s.s	m.s.	v.r.	F pr.	s.s	m.s.	v.r.	F pr.
REP	7	0.383	0.055	0.34	0.9107	0.969	0.138	0.83	0.5918
(Soil profile) SOIL	1	0.013	0.013	0.08	0.7873	0.141	0.141	0.85	0.3869
SOIL*REP	7	1.126	0.161			1.162	0.166		
Treatment combinations (RATIO)	3	6.142	2.047	35.32	<.0001	4.209	1.403	18.64	<.0001
RATIO*SOIL	3	0.079	0.026	0.46	0.7139	0.341	0.114	1.51	0.2263
Error	41	2.377	0.058			3.086	0.075		
Corrected Total	62	10.120				9.908			

	SOIL	RATIO	RATIO. SOIL		SOIL	RATIO	RATIO. SOIL	
LSD (P = 0.05)	0.239	0.118	0.167		0.243	0.134	0.189	
CV (%)	36.490				39.870			

				Root mass (g.plant-1)					
Source	d.f.	s.s	m.s.	v.r.	F pr.	s.s	m.s.	v.r.	F pr.
REP	7	0.496	0.071	1.22	0.4016	0.899	0.128	0.89	0.5607
(Soil profile) SOIL	1	0.174	0.174	2.99	0.1275	0.106	0.106	0.73	0.4213
SOIL*REP	7	0.408	0.058			1.014	0.145		
Treatment combinations (RATIO)	3	5.428	1.809	27.54	<.0001	4.402	1.467	18.19	<.0001
RATIO*SOIL	3	0.061	0.020	0.31	0.817	0.081	0.027	0.34	0.8
Error	42	2.759	0.066			3.308	0.081		
Corrected Total	63	9.327				9.810			

	SOIL	RATIO	RATIO. SOIL		SOIL	RATIO	RATIO. SOIL	
LSD (P = 0.05)	0.143	0.125	0.177		0.227	0.139	0.197	
CV (%)	38.520				47.353			

				Total biomass (g.plant-1)					
Source	d.f.	s.s	m.s.	v.r.	F pr.	s.s	m.s.	v.r.	F pr.
REP	7	0.292	0.042	0.32	0.9206	0.538	0.077	0.53	0.7903
(Soil profile) SOIL	1	0.032	0.032	0.25	0.6322	0.131	0.131	0.9	0.3749
SOIL*REP	7	0.904	0.129			1.017	0.145		
Treatment combinations (RATIO)	3	6.014	2.005	38.78	<.0001	4.463	1.488	26.37	<.0001
RATIO*SOIL	3	0.064	0.021	0.41	0.7446	0.254	0.085	1.5	0.2283
Error	41	2.120	0.052			2.313	0.056		
Corrected Total	62	9.426				8.716			

	SOIL	RATIO	RATIO. SOIL		SOIL	RATIO	RATIO. SOIL	
LSD (P = 0.05)	0.214	0.111	0.157		0.227	0.116	0.165	
CV (%)	34.490				35.799			

Chapter 4 (Competition effect)

Table C4.1. ANOVA table for soil water content (%) as effected by increasing densities of naked crabgrass and large crabgrass in competition with maize. [Glasshouse trial: Figure 4.1.]

Digitaria nuda Soil water content

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Reps stratum	7	4379.55	625.65	15.34	
Reps.*Units* stratum					
Treatments (Density)	5	1753.97	350.79	8.6	<.001
Soil type	1	808.38	808.38	19.81	<.001
Time (Weeks)	6	10010.97	1668.49	40.9	<.001
Treatment. Soil type	5	1150.88	230.18	5.64	<.001
Treatment. Time	30	813.95	27.13	0.67	0.914
Soil type. Time	6	9655.24	1609.21	39.44	<.001
Treatment. Soil type. Time	30	828.97	27.63	0.68	0.904
Residual	491	20032.16	40.8		
Total	581	43986.6			

	Treatment	Soil type	Time	Treatment. Soil type	Treatment. Time	Soil type. Time	Treatment. Soil type. Time
SE	0.604	0.348	0.652	0.854	1.597	0.922	2.258
LSD (P = 0.05)	1.661	0.959	1.794	2.348	4.393	2.536	6.213
CV (%)	11.1						

Digitaria sanguinalis Soil water content

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Reps stratum	7	6175.87	882.27	31.12	
Reps.*Units* stratum					
Treatments (Density)	5	1143.26	228.65	8.06	<.001
Soil type	1	77631.1	77631.1	2737.91	<.001
Time (Weeks)	6	12008.84	2001.47	70.59	<.001
Treatment. Soil type	5	179.89	35.98	1.27	0.276
Treatment. Time	30	1093.35	36.45	1.29	0.146
Soil type. Time	6	1143.18	190.53	6.72	<.001
Treatment. Soil type. Time	30	395.39	13.18	0.46	0.994
Residual	451	12787.7	28.35		
Total	541	96463.3			

	Treatment	Soil type	Time	Treatment. Soil type	Treatment. Time	Soil type. Time	Treatment. Soil type. Time
SE	0.503	0.29	0.543	0.712	1.331	0.769	1.883
LSD (P = 0.05)	1.398	0.807	1.51	1.978	3.7	2.136	5.232
CV (%)	10.4						

Table C4.2. ANOVA table to determine the contribution effect of naked crabgrass and large crabgrass on the rate of water use in competition with maize grown in two soil types. [Glasshouse trial: Figure 4.2]

Digitaria nuda Rate of water use (%) mean over time					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Reps stratum	4	84.174	21.044	4.89	
Reps.*Units* stratum					
Treatment	5	73.772	14.754	3.43	0.011
Soil type	1	0.071	0.071	0.02	0.899
Treatment. Soil type	5	28.457	5.691	1.32	0.272
Residual	44	189.379	4.304		
Total	59	375.852			

	Treatment	Soil type	Treatment. Soil type	
SE	0.656	0.379	0.928	
LSD (P = 0.05)	1.87	1.08	2.644	
CV (%)	12.9			

Digitaria sanguinalis Rate of water use (%) mean over time					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Reps stratum	4	97.066	24.266	3.74	
Reps.*Units* stratum					
Treatment	5	141.857	28.371	4.38	0.003
Soil type	1	947.361	947.361	146.12	<.001
Treatment. Soil type	5	28.188	5.638	0.87	0.509
Residual	44	285.276	6.484		
Total	59	1499.749			

	Treatment	Soil type	Treatment. Soil type	
SE	0.805	0.465	1.139	
LSD (P = 0.05)	2.295	1.325	3.246	
CV (%)	18.6			

184

Table C4.3. ANOVA table of dry mass per plant as influenced by increasing densities of naked crabgrass and large crabgrass [Glasshouse trial: Figure 4.3]

Nuda Dry mass per plant (g.plant[-1])

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil type	1	83.929	83.929	83.93	<.0001
Reps stratum	14	30.180	2.155		
Treatment (Density)	4	24.549	6.137	6.14	0.0004
Treatment. Soil type	4	9.009	2.252	2.25	0.0751
Residual	55	55	1		
Total	78	202.66			

	Treatment	Soil type	Treatment. Soil type	
SE	2.087	1.320	2.951	
LSD (P = 0.05)	5.89	3.731	8.341	
CV (%)	9.19			

Sanguinalis Dry mass per plant (g.plant[-1])

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil type	1	206.122	206.122	4.38	0.0409
Reps stratum	14	536.807	38.343		
Treatment (Density)	4	2218.16	554.54	11.78	<.0001
Treatment. Soil type	4	104.126	26.031	0.55	0.697
Residual	56	2636.42	47.079		
Total	79	5701.65			

	Treatment	Soil type	Treatment. Soil type	
SE	1.70	1.075	2.404	
LSD (P = 0.05)	4.804	3.038	6.794	
CV (%)	26.94			

Table C4.4. Regression analysis of maize biomass parameters when in competition with increasing densities of naked crabgrass [Glasshouse trial: Figure 4.4]

Maize dry mass (g.plant^{-1})

Source	d.f.	Clay soil				Sandy soil			
		s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
Regression	1	6821.9	6821.9	43.42	0.003	664.7	664.65	19.49	0.012
Residual	4	628.5	157.1			136.4	34.11		
Total	5	7450.3	1490.1			801.1	160.22		
R^2		89.5				78.7			
SE		12.5				5.84			

Maize Kernel weight (g)

Source	d.f.	Clay soil				Sandy soil			
		s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
Regression	1	4213.6	4213.6	33.17	0.005	2009.3	2009.31	67.98	0.001
Residual	4	508.1	127			118.2	29.56		
Total	5	4721.7	944.3			2127.5	425.51		
R^2		86.5				93.1			
SE		11.3				5.44			

Mean plant height (cm)

Source	d.f.	Clay soil				Sandy soil			
		s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
Regression	1	1053.2	1053.16	32.72	0.005	825.9	825.9	49.95	0.002
Residual	4	128.7	32.18			66.14	16.53		
Total	5	1181.9	236.38			892.04	178.41		
R^2		86.4				90.7			
SE		5.67				4.07			

186

Table C4.5. Regression analysis of maize biomass parameters when in competition with increasing densities of large crabgrass [Glasshouse trial: Figure 4.4]

Maize dry mass (g.plant-1)

		Clay soil				Sandy soil			
Source	d.f.	s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
Regression	1	9066.7	9066.7	38.56	0.003	15088	15087.6	22.15	0.009
Residual	4	940.5	235.1			2724	681.1		
Total	5	10007.3	2001.5			17812	3562.4		
R^2		88.3				80.9			
SE		15.3				26.1			

Maize kernel weight (g)

		Clay soil				Sandy soil			
Source	d.f.	s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
Regression	1	3587.9	3587.91	37.5	0.004	2581.8	2581.8	17.12	0.014
Residual	4	382.7	95.68			603.3	150.8		
Total	5	3970.6	794.13			3185.1	637		
R^2		88				76.3			
SE		9.78				12.3			

Mean plant height

		Clay soil				Sandy soil			
Source	d.f.	s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
Regression	1	77.11	77.112	18.82	0.012	63.74	63.735	12.67	0.024
Residual	4	16.39	4.098			20.11	5.029		
Total	5	93.5	18.701			83.85	16.77		
R^2		78.1				70			
SE		2.02				2.24			

Table C4.6. Regression analysis to fit the model of Cousens (1985) to maize yield loss when in competition with naked crabgrass and large crabgrass [Glasshouse trial: Figure 4.5]

D. sanguinalis Yield loss (%)

		Clay soil				Sandy soil			
Source	d.f.	s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
Regression	1	3970.94	3970.94	147.07	0.0003	4978.65	4978.65	222.606	0.0001
Residual	4	107.99	26.99			89.46	22.36		
Total	5	4078.94				5068.11			
R^2		0.973				0.982			
SE		5.196				4.729			

D. nuda Yield loss (%)

		Clay soil				Sandy soil			
Source	d.f.	s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
Regression	1	2479.62	2479.62	110.209	0.0005	2483.527	2483.527	89.209	0.0007
Residual	4	89.997	22.499			111.357	27.83924		
Total	5	2569.617				2594.884			
R^2		0.965				0.957			
SE		4.743				5.276			

187

Table C4.7. Regression analysis to fit the model of Kropff and Spitters (1991) to determine maize yield loss using total share in biomass of maize and grass species, respectively [Glasshouse trial: Figure 4.6]

D. sanguinalis Total share in dry mass (Yield loss %)									
		Clay soil				Sandy soil			
Source	d.f.	s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
Regression	1	0.399	0.399	237.4	0.0002	0.501	0.5014	464.732	<0.0001
Residual	4	0.008	0.002			0.0055	0.0011		
Total	6	0.407				0.5068			
R^2		0.979				0.989			
SE		0.041				0.033			

D. nuda Total share in dry mass (Yield loss %)									
		Clay soil				Sandy soil			
Source	d.f.	s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
Regression	1	0.2502	0.2502	185.742	0.00004	0.2452	0.2452	85.899	0.0003
Residual	4	0.0067	0.0014			0.0142	0.0028		
Total	6	0.2569				0.2594			
R^2		0.974				0.945			
SE		0.037				0.053			

188

Table C4.8. ANOVA of yield parameters of maize in competition with either naked crabgrass or large crabgrass on two soil types [Glasshouse trial: Table 4.2]

		Digitaria nuda				*Digitaria sanguinalis*			
Days to 50% silking									
Source	d.f.	s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
Soil type	1	27.250	27.250	27.25	<.0001	32.667	32.667	2.68	0.106
Reps stratum	14	14.079	1.006			285.833	20.417		
Treatment (Density)	5	42.457	8.491	8.49	<.0001	2117.208	423.442	34.73	<.0001
Treatment. Soil type	5	2.379	0.476	0.48	0.793	34.708	6.942	0.57	0.723
Residual	70	69.000	1.000			853.417	12.192		
Total	95	155.166				3323.833			

	Treatment	Soil type	Treatment. Soil type		Treatment	Soil type	Treatment. Soil type	
SE	0.281	0.1691	0.3498		0.824	0.854	1.092	
LSD (P = 0.05)	4.15	2.97	7.28		2.46	1.422	3.48	
CV (%)	1.48				4.39			

		Days to ear initiation							
Source	d.f.	s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
Soil type	1	56.585	56.585	56.59	<.0001	0.094	0.094	0.01	0.927
Reps stratum	14	21.607	1.543			429.479	30.677		
Treatment (Density)	5	46.598	9.320	9.32	<.0001	2306.677	461.335	42.03	<.0001
Treatment. Soil type	5	3.995	0.799	0.8	0.554	164.094	32.819	2.99	0.017
Residual	70	69.000	1.000			768.396	10.977		
Total	95	197.785				3668.740			

	Treatment	Soil type	Treatment. Soil type		Treatment	Soil type	Treatment. Soil type	
SE	0.326	0.179	0.359		0.958	0.896	1.301	
LSD (P = 0.05)	4.35	2.78	6.81		2.34	1.994	3.3	
CV (%)	1.45				4.06			

		Number of ears per plant							
Source	d.f.	s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
Soil type	1	2.202	2.202	7.67	0.007	0.260	0.260	1.4	0.242
Reps stratum	14	4.052	0.289			7.813	0.558		
Treatment (Density)	5	8.339	1.668	5.81	0.000	14.177	2.835	15.19	<.0001
Treatment. Soil type	5	1.225	0.245	0.85	0.517	1.927	0.385	2.07	0.08
Residual	70	19.803	0.287			13.063	0.187		
Total	95	35.621				37.240			

	Treatment	Soil type	Treatment. Soil type		Treatment	Soil type	Treatment. Soil type	
SE	0.138	0.086	0.187		0.126	0.898	0.173	
LSD (P = 0.05)	0.379	0.219	0.537		0.305	0.176	0.431	
CV (%)	36.6				36.06			

189

Chapter 5 (Critical periods of weed control)

Table C5.1. ANOVA table where maize yield was determined for different weed interference periods at Potchefstroom during 2009/2010 and 2010/2011 seasons. [Field trial 1: Table 5.1]

Yield (t.ha^{-1}) Potchefstroom 2009/2010 season					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Planting date. REP stratum					
Planting date	1	16.695	16.695	7.55	0.052
Residual	4	8.847	2.212	1.75	
Planting date. REP.*Units* stratum					
Weed control	11	96.945	8.813	6.99	<.001
Planting date. Weed control	11	29.061	2.642	2.1	0.041
Residual	44	55.475	1.261		
Total	71	207.022			

	Planting date	Weed control	Planting date. Weed control		
SEM	0.248	0.458	0.668		
LSD (P=0.05)	0.973	1.307	1.902		
CV (%)	18.3				

Yield (t.ha^{-1}) Potchefstroom 2010/2011 season					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Planting date. REP stratum					
Planting date	1	0	0	0	0.995
Residual	4	5.141	1.285	0.99	
Planting date. REP.*Units* stratum					
Weed control	11	21.475	1.952	1.51	0.165
Planting date. Weed control	11	4.173	0.379	0.29	0.984
Residual	41	53.019	1.293		
Total	68	83.479			

	Planting date	Weed control	Planting date. Weed control		
SEM	0.189	0.464	0.656		
LSD (P=0.05)	0.742	1.326	1.87		
CV (%)	24.9				

190

Table C5.2. ANOVA table where maize yield was determined for different weed interference periods at Wesselsbron during 2010and2011 seasons. [Field trial 2: Table 5.2]

Yield (t.ha^{-1}) Wesselsbron 2010/2011 season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Planting date. REP stratum					
Planting date	1	38.852	38.852	42.26	0.003
Residual	4	3.677	0.919	0.79	
Planting date. REP.*Units* stratum					
Weed control	11	49.101	4.464	3.82	<.001
Planting date. Weed control	11	6.007	0.546	0.47	0.914
Residual	44	51.469	1.17		
Total	71	149.107			

	Planting date	Weed control	Planting date. Weed control
SEM	0.16	0.442	0.619
LSD (P=0.05)	0.627	1.258	1.76
CV (%)	30.5		

191

Table C5.3. Regression analysis of the critical periods of weed control determined for Potchefstroom during 2009/2010 and 2010/2011 seasons at two planting dates (Early and Late). [Field trial: Figure 5.3]

Relative yield (%) Weedy: Potchefstroom season 2009/2010

| Source | d.f. | Early | | | | Late | | | |
		s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
Regression	2	2468	1233.98	21.43	0.007	1215.4	607.69	7.35	0.046
Residual	4	230.3	57.58			330.6	82.66		
Total	6	2698.3	449.71			1546	257.67		
Variance (%)		87.2				67.9			
R^2		0.915				0.789			
SE		7.59				9.09			

Relative yield (%) Weed-free: Potchefstroom season 2009/2010

| Source | d.f. | Early | | | | Late | | | |
		s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
Regression	2	2050.8	1025.41	25.68	0.005	1231	615.49	10.04	0.028
Residual	4	159.7	39.93			245.3	61.32		
Total	6	2210.5	368.42			1476.3	246.04		
Variance (%)		89.2				75.1			
R^2		0.982				0.834			
SE		6.32				7.83			

Relative yield (%) Weedy: Potchefstroom season 2010/2011

| Source | d.f. | Early | | | | Late | | | |
		s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
Regression	2	957.27	478.634	49.52	0.002	641.7	320.85	15.76	0.013
Residual	4	38.66	9.665			81.44	20.36		
Total	6	995.93	165.988			723.14	120.52		
Variance (%)		94.2				83.1			
R^2		0.961				0.887			
SE		3.11				4.51			

Relative yield (%) Weed-free: Potchefstroom season 2010/2011

| Source | d.f. | Early | | | | Late | | | |
		s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
Regression	2	853.5	426.75	16.88	0.011	1153.82	576.91	24.72	0.006
Residual	4	101.1	25.29			93.33	23.33		
Total	6	954.6	159.11			1247.16	207.86		
Variance (%)		84.1				88.8			
R^2		0.894				0.925			
SE		5.03				4.83			

Table C5.4. Regression analysis of the critical periods of weed control determined for Wesselsbron during 2010/2011 seasons at two planting dates (Early and Late). [Field trial: Figure 5.4]

Relative yield (%) Weedy: Wesselsbron season 2010/2011									
		Early				Late			
Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	2	712.2	356.11	6.84	0.051	4501.4	2250.69	47.54	0.002
Residual	4	208.2	52.05			189.4	47.34		
Total	6	920.4	153.4			4690.8	781.79		
Variance (%)		66.1				93.9			
R^2		0.774				0.96			
SE		7.21				6.88			

Relative yield (%) Weed-free: Wesselsbron season 2010/2011									
		Early				Late			
Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	2	712.69	356.35	16.44	0.012	4903.3	2451.66	54.55	0.001
Residual	4	86.72	21.68			179.8	44.95		
Total	6	799.41	133.23			5083.1	847.19		
Variance (%)		83.7				94.7			
R^2		0.892				0.965			
SE		4.66				6.7			

Chapter 6 (Evaluation of herbicides)

Table C6.1. AOVA table for percentage control of naked crabgrass and large crabgrass where two herbicides was evaluated in two soil types over time (Weeks after application = WAA) [Glasshouse trial: Figure 6.2]

Digitaria nuda (% Control)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Herbicides	1	319.8	319.8	0.41	0.524
Soil type	1	87769.5	87769.5	112.03	<.001
Time (WAA)	5	13574.3	2714.9	3.47	0.005
Herbicide. Soil type	1	6.9	6.9	0.01	0.926
Herbicide. Time	5	2899.2	579.8	0.74	0.594
Soil type. Time	5	8063.8	1612.8	2.06	0.073
Herbicide. Time. Soil type	5	4361.3	872.3	1.11	0.355
Residual	168	131614.6	783.4		
Total	191	248609.3			

	Herbicides	Soil type	Time	Herbicide. Soil type	Herbicides. Time	Soil type. Time	Herbicide. Soil type. Time
SEM	2.86	2.86	4.95	4.04	6.99	6.99	9.89
LSD (P=0.05)	7.98	7.98	13.81	11.28	19.54	19.54	27.63
CV (%)	37.9						

Digitaria sanguinalis (% Control)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Herbicides	1	0.08	0.08	0	0.962
Soil type	1	2236.18	2236.18	64.45	<.001
Time (WAA)	5	6337.16	1267.43	36.53	<.001
Herbicide. Soil type	1	94.86	94.86	2.73	0.1
Herbicide. Time	5	749.99	150	4.32	0.001
Soil type. Time	5	1319.62	263.92	7.61	<.001
Herbicide. Time. Soil type	5	1585.78	317.16	9.14	<.001
Residual	168	5828.6	34.69		
Total	191	18152.27			

	Herbicides	Soil type	Time	Herbicide. Soil type	Herbicides. Time	Soil type. Time	Herbicide. Soil type. Time
SEM	0.6	0.6	1.04	0.85	1.47	1.47	2.08
LSD (P=0.05)	1.68	1.68	2.91	2.37	4.11	4.11	5.81
CV (%)	6.2						

Table C6.2. ANOVA for percentage control of naked crabgrass where nine herbicides were evaluated over time (weeks after application = WAA). [Field trial 1: Table 6.2]

PRE herbicides (% Control)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	2625.1	875	1.78	
Rep.*Units* stratum					
Herbicides	2	850.7	425.3	0.86	0.442
Time (WAA)	1	936.8	936.8	1.9	0.188
Herbicides. Time	2	138.3	69.2	0.14	0.87
Residual	15	7392.9	492.9		
Total	23	11943.8			

	Herbicides	Time	Herbicides. Time
SEM	7.85	6.41	11.1
LSD (P=0.05)	23.66	19.32	33.46
CV (%)	39.6		

Pre- fb post emergence herbicides (% Control)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	410.33	136.78	1.7	
Rep.*Units* stratum					
Herbicides	2	677.43	338.71	4.21	0.035
Time (WAA)	1	11.26	11.26	0.14	0.714
Herbicides. Time	2	35.65	17.83	0.22	0.804
Residual	15	1207.23	80.48		
Total	23	2341.9			

	Herbicides	Time	Herbicides. Time
SEM	3.17	2.59	4.49
LSD (P=0.05)	9.56	7.81	13.52
CV (%)	9.5		

Post emergence herbicides (% Control)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	5418.2	1806.1	3.61	
Rep.*Units* stratum					
Herbicides	2	9649.3	4824.6	9.64	0.002
Time (WAA)	1	2450.1	2450.1	4.89	0.043
Herbicides. Time	2	2043.8	1021.9	2.04	0.164
Residual	15	7510	500.7		
Total	23	27071.3			

	Herbicides	Time	Herbicides. Time
SEM	7.91	6.46	11.19
LSD (P=0.05)	23.85	19.47	33.72
CV (%)	49.1		

Table C6.3. ANOVA table for percentage grass cover of naked crabgrass where nine herbicides were evaluated over time (weeks after application = WAA). [Field trial 1: Figure 6.3]

PRE herbicides (% Cover)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	399.4	133.1	0.78	
Rep.*Units* stratum					
Herbicides	2	1373	686.5	4	0.028
Time (WAA)	4	19202.5	4800.6	27.95	<.001
Herbicides. Time	8	396.4	49.5	0.29	0.965
Residual	34	5840.2	171.8		
Total	51	24516.5			

	Herbicides	Time	Herbicides. Time		
SEM	4.14	3.78	6.55		
LSD (P=0.05)	8.42	10.87	18.83		
CV (%)	19.4				

Pre- fb POST herbicides (% Cover)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	613.56	204.52	2.33	
Rep.*Units* stratum					
Herbicides	2	451.69	225.85	2.58	0.088
Time (WAA)	4	978.58	244.64	2.79	0.038
Herbicides. Time	8	954.77	119.35	1.36	0.241
Residual	42	3682.08	87.67		
Total	59	6680.69			

	Herbicides	Time	Herbicides. Time		
SEM	2.09	2.7	4.68		
LSD (P=0.05)	5.98	7.71	13.61		
CV (%)	51				

POST herbicides (% Cover)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	15058.5	5019.5	15.39	
Rep.*Units* stratum					
Herbicides	2	9912.3	4956.1	15.19	<.001
Time (WAA)	4	15891	3972.8	12.18	<.001
Herbicides. Time	8	2703.1	337.9	1.04	0.425
Residual	42	13701.9	326.2		
Total	59	57266.8			

	Herbicides	Time	Herbicides. Time		
SEM	4.04	5.21	9.03		
LSD (P=0.05)	11.53	14.88	25.77		
CV (%)	24.6				

Table C6.4. ANOVA table for plant height and biomass of naked crabgrass determined in nine herbicide treatments [Field trial 1: Table 6.3]

Digitarua nuda plant height (cm)					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	948.2	316.1	0.61	
Rep.*Units* stratum					
Treatment	9	33154.3	3683.8	7.1	<.001
Residual	27	14000.6	518.5		
Total	39	48103.2			
	Herbicides				
SEM	11.39				
LSD (P=0.05)	33.04				
CV (%)	43.0				

Digitaria nuda biomass (g)					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	**3**	309.1	103	0.76	
Rep.*Units* stratum					
Treatment	9	8991.5	999.1	7.4	<.001
Residual	27	3646.4	135.1		
Total	39	12947			
	Herbicides				
SEM	5.81				
LSD (P=0.05)	16.86				
CV (%)	42.0				

Table C6.5. ANOVA for percentage control of naked crabgrass where nine herbicides were evaluated over time (weeks after application = WAA). [Field trial 2: Table 6.4]

PRE herbicides (% Control)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	120.83	40.28	0.48	
Rep.*Units* stratum					
Herbicides	2	475	237.5	2.84	0.09
Time (WAA)	1	37.5	37.5	0.45	0.513
Herbicides. Time	2	25	12.5	0.15	0.862
Residual	15	1254.17	83.61		
Total	23	1912.5			

	Herbicides	Time	Herbicide. Time
SEM	3.23	2.64	4.57
LSD (P=0.05)	9.74	7.98	13.78
CV (%)	10.9		

Pre- fb POST herbicides (% Control)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	1.3333	0.4444	0.77	
Rep.*Units* stratum					
Herbicides	2	0.3333	0.1667	0.29	0.753
Time (WAA)	1	0.6667	0.6667	1.15	0.3
Herbicides. Time	2	2.3333	1.1667	2.02	0.167
Residual	15	8.6667	0.5778		
Total	23	13.3333			

	Herbicides	Time	Herbicide. Time
SEM	0.269	0.219	0.38
LSD (P=0.05)	0.81	0.661	1.146
CV (%)	0.8		

Post emergence herbicides (% Control)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	69.46	23.15	1.83	
Rep.*Units* stratum					
Herbicides	2	27729.08	13864.54	1095.77	<.001
Time (WAA)	1	1162.04	1162.04	91.84	<.001
Herbicides. Time	2	1366.58	683.29	54	<.001
Residual	15	189.79	12.65		
Total	23	30516.96			

	Herbicides	Time	Herbicide. Time
SEM	1.26	1.03	1.78
LSD (P=0.05)	3.79	3.09	5.36
CV (%)	4.8		

Table C6.6. ANOVA table for yield parameters of maize where nine herbicide treatments were evaluated [Field trial 2: Table 6.5]

Total mass of ears (% of control treatment)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	2202	734	0.53	
Rep.*Units* stratum					
Herbicides	10	48493	4849	3.5	0.004
Residual	30	41514	1384		
Total	43	92208			

	Herbicides				
SEM	18.60				
LSD (P=0.05)	53.72				
CV (%)	43.0				

Total kernel weight (% of control treatment)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	2423	808	0.54	
Rep.*Units* stratum					
Herbicides	10	51822	5182	3.43	0.004
Residual	30	45271	1509		
Total	43	99516			

	Herbicides				
SEM	19.42				
LSD (P=0.05)	56.10				
CV (%)	44.7				

Yield (t.ha^{-1}) (% of control treatment)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	2551	850	0.49	
Rep.*Units* stratum					
Herbicides	10	57657	5766	3.35	0.005
Residual	30	51702	1723		
Total	43	111910			

	Herbicides				
SEM	20.76				
LSD (P=0.05)	59.95				
CV (%)	45.4				