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The influence of two cover crop species on the growth of *Zea mays* and *Cyperus esculentus*

by

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CONTENTS

DECLARATION

I, Suzette Renè Bezuidenhout, declare that the thesis, which I hereby submit for the degree PhD in Agronomy at the University of Pretoria is my own work and has not previously been submitted by my for a degree at this or any other tertiary institution.

S.R. Bezuidenhout February 2012

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The influence of two cover crop species on the growth of *Zea mays* and *Cyperus esculentus*

by

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ABSTRACT

Cover crops not only improve soil conditions, but can also suppress weed growth. In a field experiment the influence of two cover crops, *Secale cereale* (stooling rye), and *Lolium multiflorum* (annual ryegrass), on the growth of *Zea mays* (maize) and *C. esculentus* (yellow nutsedge) was compared to the latter crop and weed's growth at three control treatments which involved weed residues left on the soil surface, application of herbicides and weed control by hoeing. Maize emergence and growth were delayed in the presence of residues of both cover crop species, especially in annual ryegrass residues. *C. esculentus* growth was significantly inhibited in the area between the maize planting rows by the cover crops for the first 14 days after maize emergence, but this growth suppressing effect diminished after 28 days. In a controlled environment study, the influence of the same cover crops, together with *Avena sativa* (oats) and three cultivars of annual ryegrass were evaluated. Maize and *C. esculentus* growth were suppressed, especially by the root residues of the cover crops with the annual ryegrass cultivar 'Midmar' being the most suppressive. Chemical analysis of the leachate of root residues indicated the presence of phenolic acids and benzoxazolin-2(3*H*)-one (BOA). It is suggested that weed growth could be reduced by the allelochemicals leached from cover crop residues but in order to achieve prolonged, effective weed control the combination of mulch retained on the soil surface and the application of herbicides will required. In an integrated weed management approach a possible reduction in the type and number of herbicide applications required for effective weed control, could be implemented.

INTRODUCTION

One of the major constraints to food production is inadequate weed management (Buhler 2002). Management efforts are generally aimed at controlling weed seedlings prior to or shortly after crop establishment as it is easier to control than killing or removing more developed weed plants. However, those weeds than develop later in the growing season still produce seed that contributes to future weed populations. Chemical control is often seen as an easy option but it is essentially a short-term solution. More emphasis should be placed on preventing weed production and reduce weed densities rather than relying primarily on chemical management (Bastiaans *et al.*, 2008).

Incorporating cover crops as part of a cultural weed management approach has various advantages. Among others, it improves the soil characteristics, reduces soil erosion (Teasdale *et al.*, 2007) and can suppress weed growth (Hartwig & Ammon 2002). In areas where crops are mainly used for animal fodder, cover crops can, in addition to being environmentally beneficial, also serve as an important source of quality forage. Cover crops should, however, fulfil at least four requirements: (i) have low production costs, (ii) provide quality forage, (iii) enhance soil characteristics accompanied by providing good soil coverage and (iv) have no negative effects on the subsequent crop (Kramberger *et al.*, 2008). Strategies to use it as a weed management tool focus on the negative effect some cover crops have on weed growth through changes in the weed growth environment and the release of secondary metabolites known as allelochemicals. These metabolites can be exploited through the phenomenon known as allelopathy (Putnam *et al.*, 1983).

Research has focused mainly on the influence of cover crop root exudates and decomposition of cereal and leguminous cover crops residues (Weston 1990). At present it is clear that crop allelopathy cannot be solely used as a weed management strategy, as the specific identified allelochemicals are non-selective and merely suppress weed growth, not killing the weeds (Bhowmik & Inderjit

2003). In addition, the concept of allelopathy is still controversial and methodological limitations and a lack of knowledge about the phenomenon hampers the application thereof (Belz 2004).

Most of the work done previously focused on evaluating the different cover crops species used in various crop production systems, desiccating the cover crops at different times and determining the suppression of weed species dominant during the trial at different populations. Results obtained are inconsistent and contradictory. This raises the question: can cover crops successfully be incorporated in a weed management system to reduce the relative fitness of weeds in a conservation tillage system without inhibiting the growth of the subsequent crop?

No information is available on the effect of cover crops on weed growth in maize production in KwaZulu-Natal (KZN). Environmental conditions in KZN and the management capabilities differ from cover crop research done elsewhere in the world and results can therefore not be extrapolated to the use of cover crops in KZN. Only the principles regarding the use of the technology can be applied. This study was conducted to evaluate the suitability of cover crops to suppress *C. esculentus* growth in maize within the framework of conservation tillage practices and to determine what the effect will be on maize development and growth. In doing so, guidelines for the successful application of sustainable integrated weed management systems may be developed.

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LITERATURE OVERVIEW

CONTENTS

CHAPTER 1

LITERATURE OVERVIEW

"Other seed fell among thorns and the thorns grew up and choked them"
Matthew 13:7

KwaZulu-Natal (KZN) is one of the nine provinces of the Republic of South Africa, characterized by the Great Drakensberg Escarpment to the west and the Indian Ocean to the east. Most of the mean annual rainfall of 845 mm is received during the summer months (October-March) with the mean maximum and minimum temperatures reaching 25.2–30.4°C and -1.4–10.7°C, respectively. An average of 6.1–7.2 hours of sunshine is received in summer (Kars *et al.*, 1999). Growing conditions are more favourable for crop production compared to most of the other provinces. Smaller areas of maize (*Zea mays*), soyabeans (*Glycine max*), dry beans (*Phaseolus vulgaris*) and potatoes (*Solanum tuberosum*) are planted in KZN, yet higher yields per hectare are produced compared to provinces with bigger production areas. On average 4.4 tons ha^{-1} of maize are produced in KZN (4.6% of the total maize production) compared to the 3.0 tons ha^{-1} in the Free State Province which has 38% more land planted to maize (Anonymous 2005).

However, not only is maize the second most important field crop besides sugarcane (*Saccharum officinarum)* in KZN, it also forms part of the agricultural activities that provide 60% of the rural population in the province with food security and a sole or complementary income. Some of the factors that affect agriculture and rural development include poverty, high input costs, uneconomical farm sizes and the quality and quantity of produce (Kars *et al.*, 1999). For instance, for a conservation tillage maize farmer in KZN to make a profit in 2010, more than nine tons of yellow maize per hectare, valued at R1255 ha^{-1} (US$1=R7), had to be produced (Whitehead & Archer 2008). Because weeds are one of the major pests in most cropping systems, it contributes not only to the higher input costs, but to the overall quantity and quality of produce. If weed

interference could be minimized not only could it lead to obtaining higher yields but also contribute to food security.

1. WEED MANAGEMENT

There is a close association between weed growth and crop production. Moss (2008) stated that the primary objective of weed management should be to better understand this association in order to improve current weed management and control programmes. Weed control is generally directed at controlling weed seedlings, not only because they are more manageable but weeds become less competitive later in the season. *Amaranthus palmeri* (Palmer amaranth) reduced maize yields between 11 and 91% as amaranth densities increased from 0.5–8 plants m^{-1} row (Massinga *et al.*, 2001), while with *Echinochloa crus-galli* (barnyard grass) interference, maize yield loss ranged between 26 and 35% when barnyard grass emerged early. Yield loss due to the latter weed was only 6% when it emerged later in the maize growth season (Bosnic & Swanton 1997).

The development of herbicides during the late 1940s and onwards, provided a simple solution to weed control, resulting in higher crop yields. Currently however, this reliance on chemical control has been critically scrutinized due to the development of herbicide resistance, the negative impact on food and environmental safety, the growth in the organic food production sector (Bastiaans *et al.*, 2008) and shifts in weed populations (Buhler 2002). In addition, the availability and less complicated management of weeds with herbicides in comparison to other methods, gives the impression that weeds can easily be controlled after crop establishment and therefore cultural and tillage methods are in many instances not considered.

Arguments against this simplification of weed management and the reliance on one weed control method have recently been published (Liebman & Davis 2000; Buhler 2002; Bastiaans *et al.,* 2008). More emphasis should be placed on reducing weed densities, preventing weed reproduction minimizing weed competition and manipulating the crop competitiveness with the weeds. Weed emergence and

density can be reduced through crop rotations, restricting light from reaching the soil surface, the formation of a physical barrier and preventing seed dispersal. Crop competitiveness can be enhanced through modification of the planting date to ensure crop emergence before the weeds, improved cultivars for rapid germination and root development, quicker canopy closure, increased planting populations (Bastiaans *et al.*, 2008) and using allelopathic crop cultivars (Belz 2004; Khanh *et al.,* 2005). Conservation tillage, together with the use of cover crops, are two important factors in adjusting existing weed management systems aimed at reducing weed fitness and improving crop yields.

2. CONSERVATION TILLAGE

Although the primary objective of tillage operations is to prepare a crop seedbed and not weed control, tillage influences weed seed germination by reducing the soil surface cover, it changes the soil temperature and moisture patterns, and it alters weed seed distribution in the soil profile (Locke *et al.*, 2002). Land users in South Africa are obliged by law to adhere to the Conservation of Agricultural Resources Act of 1983 to conserve natural resources by, among other things, combating and preventing soil erosion and maintaining the production potential of the soil. Methods such as conservation tillage, suitable conservation works and avoidance of cultivation during periods of high erosion hazard are advised (Russell 1998). Conservation tillage makes use of crop residue left on the soil surface to reduce the impact of raindrops on the soil surface and to reduce the velocity of surface runoff. In KZN, conservation tillage is practised as direct drilling when a blade cuts through the crop residue, opening a furrow into which seed and fertilizer are deposited. It has several advantages over conventional tillage systems as it reduces soil erosion, soil compaction, energy requirements, evaporation and runoff (Russell 1998; Giller *et al.,* 2009).

These advantages came at a cost to weed management as the increased complexity thereof requires a higher level of management. According to Locke *et al.* (2002) careful management with herbicides is required as more post-emergence herbicides could be needed if the weeds were allowed to establish after

crop planting. The introduction of herbicide-resistant genetically modified (GM) crops improved weed control options for conservation agriculture and it could be economically viable if only post-emergence herbicides were used (Reddy 2001). There is, however, a possibility that with the continued use of these GM crops and the limited seed migration into the field, traits such as herbicide resistance could evolve faster than under conventional tillage (Martínez-Ghersa *et al*., 2000).

Also, weed populations and seed bank dynamics can be altered by conservation tillage. Most of the weed seeds occur in the upper 10 mm of soil and very few below 100 mm (Buhler 1995; Peachy *et al.,* 2004). Small-seeded annual broadleaf and most grass species have the ability to increase prolifically because they germinate and become established when the seeds are at or near the soil surface. Summer annual species that do not require burial for establishment are also well adapted to proliferate (Buhler 1995). Conventional tillage appears to favour *Digitaria sanguinalis* (crab finger-grass), *Sorghum halepense* (Johnson grass) and *Tagetes minuta* (khaki weed), whereas conservation tillage promotes *E. crus-galli* (De La Fuente *et al*., 1999), *Amaranthus retroflexus* (redroot pigweed), *Setaria viridis* (green foxtail) (Buhler 1992), *Chenopodium album* (common lambsquarters) and *Solanum nigrum* (black nightshade) (Barberi & Mazzoncini 2001). Perennial weed populations tend to increase (Giller *et al*., 2009) and be more diverse (Locke *et al*., 2002) under conservation tillage. In KZN, *Cyperus esculentus* (yellow nutsedge), among others, can become a dominant and difficult weed to control in conservation tillage if insufficient weed control is practiced (Fowler 2000).

3. *CYPERUS ESCULENTUS*

Cyperus esculentus is an herbaceous perennial weed which can be identified by an above-ground triangular stem-like fascicle of leaves which later develops into a solid triangular rachis. Thin rhizomes and roots develop from bulbs situated at the base of the fascicle. Rhizomes consist of elongated internodes and nodal cladophylls which differentiate into tubers and shoots (Wills *et al.,* 1980; Stoller

& Sweet 1987). *C. esculentus* spreads mainly through germinating tubers, and not as effectively by sexually produced seeds, which are viable and have longevity, but seedlings lack the vigour for survival in field situations (Stoller & Sweet 1987; Lapham & Drennan 1990).

In most soils, the rhizomes of *C. esculentus* are concentrated in the upper 15 cm of soil, resulting in 80% and more of the tubers occurring in this zone. Very few tubers are found below 20 cm (Friesen & Hamill 1977; Stoller & Sweet 1987). Day length determines the vegetative and reproductive growth of *C. esculentus* periods of 8–12 hours promote tuber formation, and 12–16 hours are conducive for vegetative growth (Friesen & Hamill 1977; Williams 1982). Tubers are formed four to six weeks after seedling emergence (Stoller & Sweet 1987).

During dormancy, storage conditions influence tuber sprouting, as cool moist conditions are more favourable than dry conditions (Friesen & Hamill 1977). Differences in tuber germination and multiple sprouting are not correlated with tuber weights but tuber size does influence seedling vigour (Stoller *et al.,* 1972; Thullen & Keeley 1975). During tuber sprouting, one or more of the buds on the tuber begin to grow. A tuber can have more than one sprout forming, while others stay dormant. The number of sprouts decreases after each germination. More than 60% of the dry weight and nutrients in the tuber are used for the initial sprouting, 6–18% during the second and 2–10% during the third sprouting (Stoller *et al.,* 1972; Thullen & Keeley 1975). Removing sprouts at regular intervals reduces the shoot numbers and tuber longevity, especially when done at four-week intervals (Thullen & Keeley 1975; Stoller & Sweet 1987).

3.1 *C. esculentus* interference with crop production

Cyperus esculentus interference with crop production has been demonstrated by various authors. Cotton (*Gossypium hirsutum*) yields decreased linearly with an increase in *C. esculentus* densities. Regression equations revealed an average yield loss of 19 kg ha^{-1} for each additional initial tuber m^{-1} of crop row (Moffett & McCloskey 1998), and approximately 18 kg ha^{-1} for each additional nutsedge

plant m^{-2} (Patterson *et al.*, 1980). *C. esculentus* competition with cotton for the entire growth season reduced yields more than if the weed was present for shorter periods of time.

Stoller *et al.* (1979) reported that, although variability was seen from year to year, average maize yield losses were 8% for every 100 shoots m^{-2}. Yield reductions were more prominent in years when lower than normal rainfall was received during the growing season. Jooste and van Biljon (1980) found that the second sprouting of *C. esculentus* on the Mphumalanga Highveld in South Africa competed more with maize during the 8–16 week period than in the 0–8 week period. Maize yields were reduced by 11.4% on a Hutton soil (dry soils) and by 23.9% on an Avalon soil form (relatively wet soils). They concluded that it was possible that the first flush of nutsedge may reduce maize yields more than what they reported. Reinhardt and Bezuidenhout (2001) found that maize emergence was retarded in soil where *C. esculentus* grew for 28 days and then removed on the day the maize was sown. Maize was not affected if tubers and maize seeds were planted at the same time.

Cucumber (*Cucumis sativus*) yields were reduced when 15 or more *C. esculentus* plants m^{-2} grew with the crop. However, the cucumber plants were able to compete successfully with *C. esculentus* if the crop was seeded at optimum densities, producing an optimum stand (Johnson III & Mullinix Jr 1999). The shoot dry weight of tomatoes (*Lycopersicum esculentum*) were reduced by 34% due to *C. esculentus* competition, with no differences in the interference from below- and above-ground competition (Morales-Payan *et al.*, 2003).

Little and van Staden (2003) reported that *C. esculentus* was the main competitor for water and nutrients with an *Eucalyptus* hybrid clone, *Eucalyptus grandis* x *E. camaldulensis* in Zululand, South Africa, directly after planting, with a subsequent reduction in tree growth. Aqueous extracts of tubers and foliage of immature and mature *C. esculentus* plants inhibited the growth of the essential ectomycorrhiza, *Boletus maxaria* on agar medium isolated from patula pine

(*Pinus patula*) roots (Reinhardt & Bezuidenhout 2001). Their findings proposed that the interference of *C. esculentus* with seedling development of patula pine was indirect, through the primary inhibition of the ectomicorrhizal symbiont *B. maxaria* by allelochemicals released from the weed.

Although Jangaard *et al.* (1971) did not investigate the allelopathic effects of *C. esculentus*, they identified certain phenolic compounds in the tubers that are known for their allelopathic potential. Compounds identified included p-coumaric, ferulic, p-hydroxybenzoic, syringic, vanillic, salicylic, protocatechuic and caffeic acids, with p-coumaric and ferulic acids in higher concentrations. Allelopathic effects were suggested when extracts and dried material of *C. esculentus* and *C. rotundus* (purple nutsedge) reduced the growth of cereals, vegetables and soyabeans (Tames *et al.,* 1973; Meissner *et al.,* 1979; Drost & Doll 1980).

3.2 Control measures for *C. esculentus*

Shading reduces the total number of shoots and tubers, dry weight, plant height and leaf area of *C. esculentus* due to its C4 photosynthesis pathway. *C. esculentus* growth was significantly increased when plants were removed from the shade into full sunlight (Patterson 1982). Both Keeley and Thullen (1978) and Santos *et al.* (1997) found that 20–30% shade was detrimental to growth. In contrast, Jordan-Molero and Stoller (1978) reported that 30% shade did not influence the weed's growth. Various crops planted at different plant populations reduced the above-ground growth of *C. esculentus* due to the low intensity of light reaching the weed. Ghafar and Watson (1983) showed that increasing the maize population from 33 300 to 133 300 plants ha^{-1} significantly reduced the *C. esculentus* above-ground biomass, tuber number, weight and height at the end of the growing season, with a concomitant significant increase in maize yield. Maize, barley (*Hordeum vulgare*), hemp (*Cannabis sativa*) and stooling rye (*Secale cereale*) reduced the above-ground biomass and density of *C. esculentus* secondary shoots in comparison with when a crop was absent (Lotz *et al.*, 1991).

Crops that create a regime of low light intensity during a long *C. esculentus* growth period suppressed tuber formation more strongly than crops that shadow the weed for a relatively short period of time (Lotz *et al.*, 1991). Various other authors confirmed that shading suppresses tuber formation (Jordan-Molero & Stoller 1978; Keeley & Thullen 1978; Patterson 1982; Li *et al.,* 2001). However, according to Stoller *et al.* (1979), maize planted in 75-cm rows did not provide enough shade to prevent *C. esculentus* from producing tubers. This is supported by Santos *et al.* (1997). Reductions in total leaf area were primarily the result of less leaves produced, as well as them being thinner compared to those in full sunlight (Patterson 1982). Thomas (1969) found that temperature had the greatest effect on *C. esculentus* tuber survival, while the duration of desiccation did not significantly influence tuber survival. A combination of temperature and humidity was more effective in killing tubers than either treatment alone.

Although Stoller and Woolley (1983) and Stoller and Sweet (1987) stated that mulching would not be effective for growth suppression because the leaves of *C. esculentus* have sharp tips that could penetrate hard surfaces, Webster (2005) found that pots covered with 32 µm black-opaque and colourless-clear polyethylene mulches restricted nutsedge growth, as very few shoots emerged through the mulch. The biomass of *C. esculentus* shoots under the mulch was lower compared to the non-mulched treatment, with shoots under the black having a greater biomass than those under the clear mulch. Both mulches reduced tuber production to nearly half of the non-mulched control. Ormeño-Núñez *et al.* (2008) concluded that a dense stooling rye mulch between rows in a vineyard reduced *C. esculentus* growth by 81%.

The limitation of herbicide options for *C. esculentus* control in conservation agriculture and the variability of chemical control (Jooste & van Biljon 1980), creates the opportunity to incorporate the use of cover crops in a weed management system to reduce the weeds' fitness in order to increase crop competitiveness

4. COVER CROPS

If the reliance on herbicides for weed management is reduced or eliminated, weed suppression must be approached from a crop cultivation perspective. Interest in the use of cover crops has been motivated primarily to produce crops in a more environmentally sustainable manner. Some of the benefits of cover crops include improving water infiltration, soil structure, reducing soil erosion, releasing nutrients upon decomposition, increasing the soil organic matter and preventing the leaching of N from the previous season (Liebman & Davis 2000). Cover crops can be grown in rotations after the main crop has been harvested or could grow simultaneously during part or all of the main crop season. For the purpose of reducing *C. esculentus* growth in a maize conservation tillage system in KZN, the term cover crop refers to crops planted in autumn after the main crop has been harvested and then killed during the following spring before planting the next main crop into the residues. The cover crop residues remaining on the soil surface could suppress weed growth through environmental and chemical interference.

4.1 Weed suppression due to environmental interference

Seed germination is dependent on adequate, but not excessive, supply of water, suitable oxygen:carbon dioxide ratio, and optimum temperatures and light (Monaco *et al.*, 2002). Cover crop residues remaining on the soil surface can physically modify the germination environment by intercepting light and rain and interfering with the heat and water transfer between the soil and atmosphere (Teasdale *et al.*, 2007).

Exposure to light is one of the basic requirements of many weed seeds to germinate. Residues on the soil surface would intercept the incoming radiation promoting dormancy of species with a light requirement. According to Teasdale and Daughtry (1993) light transmission was more obstructed by live hairy vetch *(Vicia villosa)* plants than desiccated hairy vetch material, influencing the suppression of weed growth. Changes in the light spectrum reaching the seed under plant residue could affect the light quality, thereby suppressing germination and growth of photo-dormant species (Teasdale & Mohler 1993). Red

light converts phytochrome to an active form, promoting germination, while far-red light inactivates phytochrome, thus inhibiting germination. Most weed seeds germinate when exposed to the red light portion of sunlight and not in darkness. However, desiccated cover crops have limited influence on the red:far red light ratio due to the absence of chlorophyll (Teasdale & Mohler 1993).

Plant residues on the soil surface lower the soil surface temperature by acting as insulation from the air temperature and intercepting solar radiation thus delaying cooling of the soil surface more than heating (Teasdale & Mohler 2000). Not only could germination be delayed at lower maximum soil temperatures due to the residues but the temperature of the residues itself could suppress germination. Teasdale and Mohler (1993) recoded residue temperatures of 41°C when the air temperature was 37°C. Changes in the soil temperature may enhance mineralization rates, thereby influencing nutrient availability (Facelli & Pickett 1991).

Plant litter on the soil surface may retain some rain water, depending on the litter characteristics (Facelli & Pickett 1991), thereby limiting the amount of water available for germination. During dry periods soil moisture under the residues could be higher creating favourable conditions for germination. However, saturated conditions could reduce germination. *C. album* and *S. viridis* establishment was reduced by soil moistures above field capacity under hairy vetch residues (Teasdale 1993).

The residues on the soil surface may obstruct seedling roots reaching the soil thereby reducing the growht of seeds and sprouts. Seedlings emerging from beneath the residues need to devote more energy penetrating it, leading to higher seedling mortalities. Small seeded species are more sensitive to covering, especially at the cotyledon stage. Once the stored resources of the seed are depleted no energy is available for growth (Baerveldt & Ascard 1999; Liebman & Davis 2000). The degree of weed control provided by the residues is likely to be

influenced by the weed species and growth stage, the thickness of soil cover and the soil type.

4.2 Weed suppression due to chemical interference

The allelopathic effects of cover crops on weed growth is the primary means of chemical interference and have been documented (Weston & Duke 2003). Plants interfere directly and indirectly with their neighbours, with a subsequent reduction in growth in any one or both of them as a consequence. Direct effects are attributed to competition and allelopathy, while indirect effects are attributed to changes in the growth environment due to physical effects and the presence of pests and diseases (Hoffman *et al*., 1996). With competition, growth factors are diminished, while with allelopathy, chemical compounds that are released into the environment affect plant growth (Khanh *et al*., 2005).

4.2.1 Allelopathy research

The root exudation and leaching of allelochemicals from a range of crops employed as cover-, smother-, companion- or intercrops form the basis of a weed management strategy involving allelopathy (Belz 2004; Khanh *et al.,* 2005). However, the discipline of allelopathy has had its share of controversy, in part due to the following limitations: (a) complex research methodology is required for distinguishing between allelopathy and competition (Belz 2004), (b) the widely held assumption that all chemicals extracted from plants would exhibit allelopathic characteristics, and (c) the assumption that the mere presence of allelochemicals in plant tissue presents strong evidence for allelopathy (Inderjit & Callaway 2003).

In the past, to prove that allelopathy was the cause of plant growth inhibition, unrealistic bioassays using leachates or extracts of plant parts in artificial conditions have been used (Foy & Inderjit 2001; Olofsdotter *et al.,* 2002). Bioassays are important in the study and demonstration of allelopathy. Therefore, in order that experiments produce more convincing evidence for the existence and function of allelochemicals they should meet the following criteria: (a) showing allelochemicals being released from the donor plant and arrives in

functional concentrations under natural conditions at the receiver plant, (b) determination of the fate and persistence of allelochemicals in soil, (c) elucidation of the uptake mechanism of the receiver plant and its subsequent response (Blum 1999; Inderjit & Callaway 2003). To discover whether or not these subunits work together, a field study is necessary (Inderjit & Weston 2000; Khanh *et al.,* 2005), but the evaluation of the contribution of each phenomenon to the overall effect in a field situation is difficult and therefore selection of allelopathic cover crop plants under field conditions is not an option (Foy & Inderjit 2001; Olofsdotter *et al.,* 2002). In evaluating the ability of rice to control weed growth, research was focused on bioassays and field work that led to a correlation between growth inhibition and allelochemical release, which formed the basis of a subsequent international breeding programme for developing competitive rice cultivars (Olofsdotter 2001).

4.2.2 Allelochemicals

All plants synthesize secondary metabolites which are generally considered not important for primary metabolic processes essential for a plant's survival. These metabolites represent a vast number of biologically active compounds, of which some are allelopathic and are referred to as allelochemicals. The allelopathic effect on plants is often the result of a combination of these chemicals released together, as individual compounds are often present in concentrations below their inhibition thresholds (An *et al.,* 1998; Inderjit & Nayyar 2002).

Allelopathic plants do not develop in isolation and environmental conditions influencing plant growth will directly affect allelochemical production and expression. The extent of their phytotoxicity depends on soil characteristics, abiotic and biotic factors, the donor and target plant species and cultivars used (Inderjit & Nayyar 2002).

Adsorption, desorption and degradation of allelochemicals in soil are just as common a phenomena as with herbicides, and therefore, soil texture, organic and

inorganic matter, moisture and micro-organisms as well as allelochemical solubility in water will affect their phytotoxic activity in the soil (Inderjit *et al.,* 2001; Kobayashi 2004). A recent example of this is the abiotic and biotic variables that degraded the allelochemical parthenin released from the alien invader plant *Parthenium hysterophorus* (Parthenium), causing it to have short but variable half-lives in soil, depending on temperature, moisture and microbial activity (Belz *et al*., 2009). Soil micro-organisms can use allelochemicals as a food source and if allelochemicals are released, the micro-organism population can increase in response. Plant growth inhibition can be the result not only of the allelochemicals present but also because the micro-organisms can transform these compounds to new chemicals of lower or higher bioactivity. In addition, microbes can immobilize nutrients, with subsequent reduction in plant growth (Schmidt & Ley 1999).

The abiotic factors water and nutrient content, temperature and applied herbicides have a significant influence on the availability of allelochemicals. In a review by Tang *et al.* (1995) various examples were given in which stress factors caused an elevation in allelochemicals. Gershenzon (1984) came to the conclusion that the accumulation of secondary metabolites under stress conditions must be an adaptive response to conditions under which the function of these compounds becomes important. Einhellig (1987) showed how certain herbicides synergize or supplement the activity of allelochemicals, which can have implications for conservation tillage as it is dependent on herbicide use. The fate of allelochemicals under stress cannot be generalized. The availability of growth resources for donor and target plants can be influenced by the presence of allelochemicals. Donor plants may be less influenced due to their adaptation to the stress, while target plants could lack this ability. Damage is therefore caused by abiotic stress or allelochemicals, or by both (Inderjit & Nayyar 2002).

Choosing the cover crop species and cultivar would also have an impact on the allelopathic effect produced on weed species (Weston & Duke 2003). Differences in their ability to suppress weed growth were reported for, among others, stooling

rye and its different cultivars (Pérez & Ormeño-Núñez 1993; Burgos *et al.,* 1999), wheat (*Triticum aestivum)* (Tollenaar *et al*., 1993) and clover (*Triflolium* sp) (Creamer *et al*., 1996).

Reports on the influence of allelochemicals on plants most frequently identified effects which are readily observed in the field or under controlled conditions. Delayed or inhibited germination and the stimulation or inhibition of root and shoot growth are often reported (Rizvi *et al*., 1992). The major difficulty is to separate secondary effects from primary causes. An important question that always remains is whether or not the inhibitor reaches the active site in the plant in sufficient concentration to specifically influence that reaction, and if other processes may also be affected.

The mode of action of a chemical can broadly be divided into a direct and an indirect action (Rizvi *et al*., 1992). Effects through the alteration of soil properties, nutritional status and an altered population or activity of micro-organisms and nematodes represent the indirect action. Direct action involves the biochemical/physiological effects of allelochemicals on various important processes of plant growth and metabolism. Some of the processes influenced by allelochemicals are:

- reduction in mineral uptake;
- inhibition of cytology and ultrastructure;
- inactivation of phytohormones and upsetting their balance, and
- inhibition of photosynthesis, respiration and protein synthesis (Rice 1984; Putnam 1985).

Under natural conditions the action of allelochemicals seems to revolve around a fine-tuned regulatory process in which many such compounds may act together on one or more of the above processes (Rizvi *et al*., 1992).

4.3 Cover crops used

4.3.1 Cereals: stooling rye and oats

Stooling rye is an annual cereal crop with a fibrous root system and hollow stems that can reach heights of 80–180 cm, depending on the cultivar. As a green plant it is utilized as a green manure and animal fodder, especially during the winter, while the grain is used for flour and alcohol production. In the cooler regions of KZN it is planted as animal fodder in autumn and used from May to September. Oats is a tufted winter-growing annual and in South Africa, oats are mainly produced as a winter grazing or green feed and produce the highest amount of forage per unit area. Planting commence in March and April with the main growth from March to October (Dickinson *et al*., 1990).

Stooling rye is preferred as a cover crop due to its potential to produce abundant biomass that suppress weed emergence and growth (Koger *et al*., 2002). In the absence of herbicides, grass control by a stooling rye cover crop increased by 46–61% above the no-cover or conservation tillage system (Yenish *et al*., 1996), while the biomass of *C. album, Polygonum aviculare* (prostrate knotweed) and *Fallopia convolvulus* (climbing knotweed) were reduced by the stooling rye cultivar 'Forrajero-Baer' (Pérez & Ormeño-Núñez 1993).

Oats reduced the number of individuals of *Picris echioides* (bristly ox-tongue) by 94% (de Bertoldi *et al*., 2009). Weed density was reduced by oats and grazing vetch (*Vicia dasycarpa*) with 90 and 80% respectively while reduction by lupins (*Lupinus angustiflolius*) were less successful at only 23% compared to the control plots (Murungu *et al*., 2010). In trials done by Seavers and Wright (1999) oats were more suppressive than barley and wheat. They concluded that the suppressive effect was not only due to the canopy that was formed as the oats had the slowest canopy development of the test species but retained their weed growth reduction throughout the growing season. This was confirmed by Fourie *et al.* (2006) who reported effective long-term control of summer weeds with oats, rye and black oats (*Avena strigosa*).

The influence of residues on crop growth and weed suppression varies with the time of cover desiccation, resulting in partial suppression of specific weed species. In tomatoes, stooling rye provided 4–8 weeks control after planting, depending on the season and time of desiccation (Smeda & Weller 1996). Soyabean yields were significantly higher when planted into stooling rye residues that were killed two weeks before planting compared to treatments that were planted a day after the stooling rye was killed (Liebl *et al.*, 1992). This was confirmed by Raimbault *et al.* (1990) who found that crop growth was retarded if planted into stooling rye immediately after the stooling rye was killed. The effect was increased when used in a no-till system compared to a conventional tillage system. According to Yenish *et al.* (1995), the residual effect of killed stooling rye does not persist beyond 170 days.

The reduction in weed growth is further influenced by cultivar choice although differences of opinion exist about the attributes of different cultivars. Walters *et al.* (2005) found that the cultivars 'Elbon' and 'Matice' provided better weed suppression due to their higher yields and soil coverage, while Tollenaar *et al.* (1993) found that 'Kodiak' and 'Gordon' reduced maize yields the most, despite their low yields and therefore low biomass. They attributed it to the higher below-ground biomass. In addition, higher benzoxazolinone content were found in 'Bonel' and 'Aroostok', although they did not have the highest yields (Burgos *et al.*, 1999). The cultivar 'Wheeler' reduced maize heights and yields when the maize was planted immediately after the stooling rye was killed (Raimbault *et al.*, 1990) The benzoxazolinone content of 'Bates' increased between 30 and 60 days after planting and decreased thereafter (Burgos *et al.*, 1999). The differences in weed suppression could be attributed to the decomposition products of stooling rye tissue of different ages. According to Wójcik-Wojtkowiak *et al.* (1990), tillering plants gave the highest level of inhibition, but crop residues did not exhibit toxicity. The level of toxicity was found to be dependent on decomposition time and increase as tissue degraded, reaching a maximum after 3-4 weeks of degradation before decreasing.

Favonoids and saponins have been identified in oats (de Bertoldi *et al.*, 2009), while one of the allelochemical groups responsible for the allelopathic expression of stooling rye is collectively called benzoxazolinones or benzoxazinones (Belz 2004). The production of BOA (benzoxazolin-2(3*H*)-one) involves two precursors, a benzoxazinoid acetal glucoside and its aglucone (Figure 1). The acetal glucosides DIBOA-Glc are transformed to aglucone DIBOA (2,4-dihydroxy-2*H*-1,4-benzoxazin-3(4H)-one which, in turn, forms BOA (Sicker *et al.*, 2004). Weed control in the field could be attributed to the formation of AZOB (azoperoxide) which would increase the phytotoxicity.

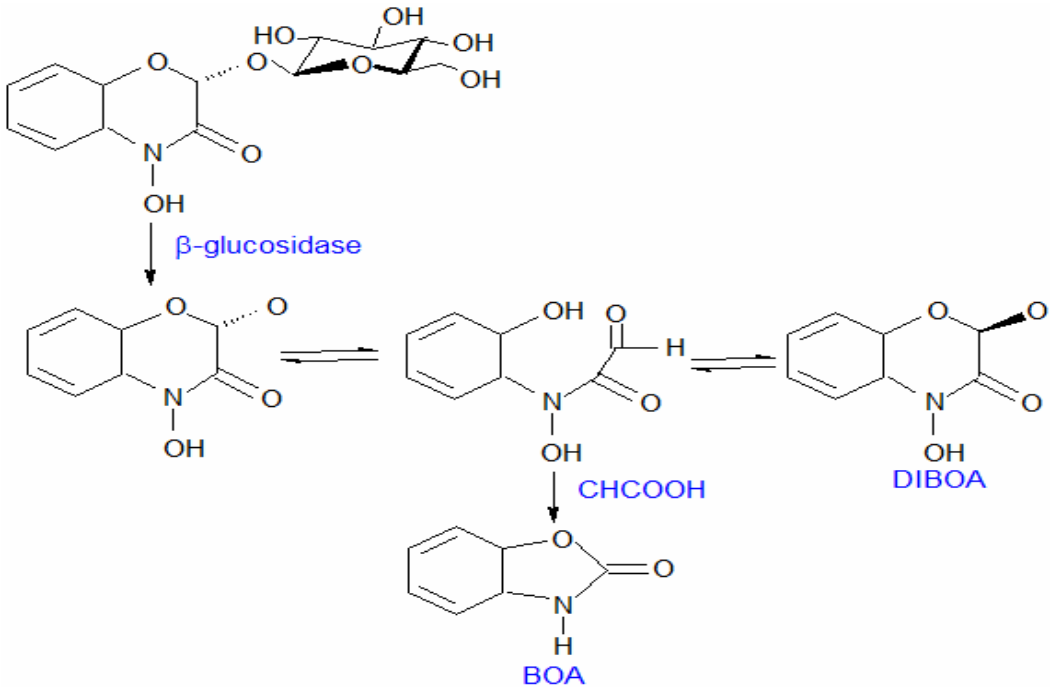

FIGURE 1 Chemical formation of BOA from DIBOA (Sicker *et al.*, 2004)

Glucosides are regarded as non-toxic in juvenile plants and are stored in the vacuole until needed. Aglucones are released when plants are attacked by insects or fungi, when residues are being decomposed, and through root exudation (Yenish *et al.*, 1995; Burgos *et al.*, 1999). DIBOA is chemically unstable in solutions and during decomposition and is therefore converted to BOA. According to Burgos and Talbert (2000), BOA is not solely responsible for the phytotoxic reactions in plants.

Low concentrations of allelochemicals are rapidly broken down by microbes in the soil and are adsorbed onto the soil colloids (Kobayashi 2004). The continuous release of allelochemicals from the donor plants into the rhizosphere will compensate for these loss factors. It must be borne in mind that an effect on the receptor plant would only be noticed if the plant is susceptible to the allelochemicals in such a way that it would cause damage or result in the death of the plant. Chiapusio *et al.* (2004) and Belz *et al.* (2007) confirmed that the effect of allelochemicals is dependent on the concentration. Typically, at the higher concentrations the growth inhibiting effects are most severe, whereas growth stimulation is possible at the lowest concentrations of a particular compound. BOA is also more concentrated in certain plant parts than in others. Rice *et al.* (2005) confirmed work done by Tang *et al.* (1975) that more BOA occurs in stooling rye shoots than in the roots.

According to Chase and Nair (1991), it is very difficult to determine the concentrations of compounds at a specific point in time in nature. These compounds can function on their own or in combination with others. Benzoxazolinones should be resistant to microbial transformation to have any allelopathic effect (Yenish *et al.*, 1995). The allelopathic activity in the field should be high due to exudation by roots and decomposition of material. Microbes convert BOA into AZOB (2,2'-oxo-1,1'-azobenzene), which has a higher toxicity than DIBOA and BOA (Nair *et al.,* 1990; Chase & Nair 1991). Rice *et al.* (2005) identified DIBOA and BOA in shoot tissue of stooling rye while DIMBOA glucose ((2R)-2-beta-D-glucopyranosyloxy-4-hydroxy-7-methoxy-(2H)-1,4-benzoxazin-3(4H)-one) and MBOA (2,4-hydroxy-7-methoxy-(2H)-1,4-benzoxazin-3(4H)-one) were more prevalent in root tissue. Lettuce (*Lactuca sativa*) was more affected by crude extracts of the shoot tissue than the root tissue.

In a study conducted by Burgos and Talbert (2000) results showed that small-seeded seeds are more sensitive to benzoxazolinones than large-seeded species. However, there was variation between the reactions of small seeds. Therefore, seed size alone apparently does not account for the variability in allelopathic

expression. The root and stem elongation of cucumber was more effected by DIBOA than BOA in a petri dish bioassay (Burgos *et al.*, 2004).

4.3.2 Annual ryegrass

Annual ryegrass (*Lolium multiflorum*) is an annual pasture species which provides additional fodder to animals. Cultivars are divided into two categories, Italian and Westerworld cultivars. Italian ryegrass cultivars need vernalisation in order to become reproductive and can be sown in autumn or spring. If planting occurs in spring a longer grazing period is obtained. Westerworld types are sown in autumn and will become reproductive as soon as the day length increases and they then flower in spring. The two types of cultivars are further divided into diploids and tetraploids, with diploids having narrow, shorter leaves, but being more hardy and with greater density than the tetraploids (Dickinson *et al.*, 1990).

Decomposition of annual ryegrass residues is slow and residues remain on the soil surface for longer (Reddy 2001). Despite this, weed growth suppression is variable, as *Brachiaria ramose* (browntop millet) suppression declined over time, but *C. esculentus* growth remained constant. In comparison with other cover crops tested, annual ryegrass suppressed weed growth the most (Burgos & Talbert 1996; Reddy 2001).

Interference from annual ryegrass is ascribed to the finer root system of annual ryegrass enlarging the root area, allowing more nutrients and water to be extracted (Liebl & Worsham 1987; Stone *et al.,* 1998). In addition, nitrogen mineralization can be exploited better because of a more effective root system (Kramberger *et al.*, 2008). Data are lacking regarding the allelopathic potential and identity of putative allelochemicals in annual ryegrass even though circumstantial evidence exists that the species is allelopathic (Smith & Martin 1994). Various allelochemicals have been identified in other Poaceae species (Sánchez-Moreiras *et al.*, 2004).

Despite the potential for weed suppression and other advantages a cover crop offers, annual ryegrass residues reportedly has a negative influence on the growth of wheat (Appleby *et al*., 1976), southern pea (*Vigna unguiculata*) (Burgos & Talbert 1996) and soyabean (Reddy 2001) growth as yields were reduced when planted into the residues. However, (Russo *et al.,* 2006) stated that environmental conditions, more than the presence of annual ryegrass residues, reduced pumpkin *(Cucurbita* spp*)* yields.

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CHAPTER 2

Influence of cover crops *Secale cereale* and *Lolium multiflorum* on the growth of *Zea mays* and *Cyperus esculentus* under field conditions

CONTENTS

LIST OF TABLES AND FIGURES

CHAPTER 2

Influence of cover crops *Secale cereale* and *Lolium multiflorum* on the growth of *Zea mays* and *Cyperus esculentus* under field conditions

1. INTRODUCTION

In KZN, crops are produced on 5.2% of high potential soils, whilst 2.7% of production is on low potential soils. However, land degradation is increasing at an alarming rate due to, amongst other factors, soil erosion and bush encroachment (Bennet, 2008, Personal communication)[1]. The area available for crop production on high potential soil is therefore decreasing, forcing producers to incorporate more marginal areas into production. One major challenge facing crop producers in KZN is to increase food production in a sustainable manner by incorporating new production practices while at the same time dealing with higher input costs. Inadequate weed control could lead to lower crop yields impacting on sustainability and costs.

In KZN, *Cyperus esculentus* (yellow nutsedge), among other weeds, can become dominant and difficult to control in a conservation tillage system if inadequate weed control is applied. It is a herbaceous perennial weed that is characterized by prolific vegetative growth which produces a complex underground system of rhizomes and tubers (Gifford & Bayer 1995). Interference by *C. esculentus* reduces yields of maize (*Zea mays*) (Stoller *et al.*, 1979), cotton (*Gossypium hirsutum*) (Moffett & McCloskey 1998) and vegetables (Johnson III & Mullinix Jr 1999) through competition (Stoller *et al.*, 1979) and allelopathy (Drost & Doll 1980). Aqueous extracts of tubers and foliage of immature and mature *C. esculentus* plants inhibited the growth of the essential symbiotic ectomycorrhiza *Boletus maxaria* isolated from patula pine (*Pinus patula)* roots on agar medium (Reinhardt & Bezuidenhout 2001). Results suggested that the interference potential of *C. esculentus* varies with its growth stage.

[1] R.G. Bennet, DAEARD, Private Bagx9059, PMB, 3200

Short-term weed control efforts concentrate on controlling existing weed populations while long-term objectives must aim to prevent and reduce weed growth. Although previous studies have shown that inadequate weed control, especially at an early stage in crop development, can reduce crop yields (Hall *et al.*, 1992; Halford *et al.*, 2001), Ryan *et al.* (2009) and Davis *et al.* (2005) found that the yields of crops growing in organic systems, which depended more on cultural weed control methods, were not compromised by higher weed biomass levels. They concluded that the crop competitiveness and improved yield capacity were responsible for the apparent tolerance to weed competition. Cover crops can from part of a cultural management approach to limit the number of competitive weed species through influencing weed density and/or development (Liebman & Davis 2000).

According to Teasdale *et al.* (2007), cover crops improve the soil structure, increase organic material, reduce soil erosion and improve water infiltration. It also suppresses weed growth by creating a physical barrier to growth and a change in microclimatic conditions (Teasdale 1993; Teasdale & Mohler 2000). The degree of weed suppression depends on the cover crop species, the thickness of the mulch and the management system used, because different weed species react differently to the residues of cover crops (Creamer *et al.*, 1996). The most widely used cover crop species include stooling rye (*Secale cereale*), hairy vetch (*Vicia villosa*), wheat (*Triticum aestivum*) and *Trifolium* species. Dhima *et al.* (2006) found that stooling rye, triticum (x *Triticosecale*) and barley (*Hordeum vulgare*) reduced the emergence of *Echinochloa crus-galli* (barnyard grass) and *Setaria verticillata* (bristly foxtail) in the field by 27–80% and 0–67%, respectively, in comparison to cover crop mulch-free plots, without affecting maize emergence.

In South Africa, limited work has been done on the ability of cover crops to suppress weed growth in a crop situation. Fourie *et al.* (2006) evaluated different cover crops for weed control in vineyards in the Western Cape, while Little and van Staden (2003) have done work on the use of legumes to suppress weed

growth in forestry. Ferreira and Reinhardt (2010) explored the possibility of using allelopathic crop residues to suppress herbicide resistant weeds in the Western Cape. No information on the ability of cover crops to suppress weed growth in a crop situation in the KZN region is available. The objectives of this study were to determine the ability of annual ryegrass and stooling rye as winter-grown cover crops to suppress *C. esculentus* growth and evaluate the subsequent influence on maize germination and growth in a field situation.

2. MATERIALS AND METHODS

2.1 Experimental site

A field experiment was carried out from 2003 to 2007 at the Cedara Research Centre of the KwaZulu-Natal Department of Agriculture, Environmental Affairs and Rural Development, South Africa (latitude 29°32'S; longitude 30°16'E; altitude 1051 m). The mean annual rainfall is 880 mm, of which about 130 mm falls in winter (April to August) and about 750 mm in summer (September to March). The annual A-pan evaporation is 1655 mm and 6.8 hours of sunshine per day are received during October to March (Camp 1999). The climatic data for 2003 to 2007 was received from the South African Weather Service automatic weather station at Cedara. The soil is of the Avalon form, orthic A on a yellow-brown apedal B and soft plintic B horizon. Soil analysis showed an average of 37% clay, 20% silt, 43% sand and 2.59% organic matter. The average pH (KCl) and acid saturation during the experimental period was 4.53 and 6.88% respectively. Soil analysis results for each growing season the experiment was conducted appear in Table 1. During the 2006 and 2007 growing seasons, soil analysis revealed certain plots with an average acid saturation of 25% and a pH (KCl) of 4.15. Dolomitic lime, at 2 t ha^{-1}, was applied to these plots. After application the average acid saturation of these plots fell to 11% and the pH (KCl) increased to 4.39.

TABLE 1 Nutrient content of soil for each growing season from 2003 to 2007

Season	P	K	Ca	Mg	Total cations	Acid saturation	pH
		(mg L^{-1})			(cmol L^{-1})	(%)	(KCl)
2003	9.41	113.45	808.18	198.36	6.13	2.86	4.67
2004	12.54	89.17	804.88	223.92	6.44	5.96	4.57
2005	13.36	130.27	773.23	204.92	6.23	6.15	4.52
2006	18.95	121.18	725.05	199.59	6.08	9.45	4.45
2007	20.85	145.71	760.90	186.96	6.26	9.56	4.46

2.2 Treatments

Dates on which major operations occurred are listed in Table 2. In 2006, cover crop planting was delayed due to the late harvesting of the 2005 season maize. In order to avoid a mid-summer drought during pollination, maize was planted earlier in 2006 and 2007. Two cover crop species, namely stooling rye cultivar 'Agri Blue' and annual ryegrass (*Lolium multiflorum*) cultivar 'Midmar', were planted in 150 mm spaced rows with a Connor Shea Pasture Drill, except in 2003, when it was broadcast onto the different plots. The ryegrass and stooling rye were drilled at 30 and 90 kg ha^{-1}, respectively. The broadcast rate was one and a half times the drilling rate. After seeding, fertilizer was broadcast separately on each plot and the seedbed was rolled with a Cambridge roller. Nitrogen (350 kg ha^{-1}), phosphorus (20 kg ha^{-1}) and potassium (160 kg ha^{-1}) were applied as NPK (2:3:4) (40%), with 0.5% added zinc. The balance of nitrogen (336 kg ha^{-1}) was applied as a top-dressing in the form of limestone ammonium nitrate (LAN) (28%) and potassium (133 kg ha^{-1}) as potassium chloride (KCl) six weeks after cover crop planting. Glyphosate-isopropylamine (Roundup SL, 360 g a.i. L^{-1}, Monsanto) was applied at 2160 g a.i. ha^{-1}, using a knapsack sprayer equipped with a floodjet nozzle (Lurmark Polijet 110° AN1.8) directly after planting, at a pressure of 200 kPa, to control any weeds growing at that stage. The high application rate was used as lower rates did not kill the annual ryegrass sufficiently. Supplementary irrigation, with a floppy sprinkler system, was

applied according to soil moisture measurements taken with a Diviner 2000 Series moisture probe from Sentek during the cover crop growth period as the winter rainfall is too low for adequate growth. No additional pre- or post-emergence herbicides were applied to the cover crop treatments during their growth cycle. The cover crops were grown until maturity at 23 weeks, after which they were killed with glyphosate-isopropylamine applied in the same manner as described above.

Three control treatments, namely herbicide-treated (pre- and post-emergence), hand-weeded (hoeing) and non-weeded were included in the experimental design. The pre-emergence herbicide combination consisted of S-metolachlor (Dual S Gold EC, 915 g a.i. L^{-1}, Syngenta) and atrazine/terbuthylazine (Suprazine SC, 300/300 g a.i L^{-1}, Dow AgroScience) at 1189.5 and 1200 g a.i. ha $^{-1}$, respectively. Application was done at planting with a knapsack sprayer equipped with a floodjet nozzle (Lurmark Polijet 110° AN1.8) at 200 kPa. Post-emergence herbicides were applied six weeks later. These were paraquat dichloride (Gramoxone, SL, 200 g a.i. L^{-1}, Syngenta) and ametryn (Ametryn 500 SC, 500 g a.i. L^{-1}, Dow AgroScience) applied at 600 and 1000 g a.i. ha $^{-1}$, respectively, with an even flat nozzle (Teejet TP 8003E) at 200 kPA. Hand-weeding by hoeing was done as soon as 5% visual weed cover occurred. In the weeds plots no manual or chemical weeding was done and therefore weeds occurring on these plots represented the natural weed spectrum at the experimental site.

Maize planting furrows were drawn with a V-shaped hoe. Fertilizers were applied to each treatment, according to the soil analysis done on samples. Soil samples were collected twice during the growing season in the different treatments; after spraying the cover crops with glyphosate-isopropylamine and after maize harvesting. Nitrogen (140 kg ha^{-1}) and phosphorus (20 kg ha^{-1}) were applied as NPK (2:3:4) (40%) with 0.5% added zinc and the balance of nitrogen (110 kg ha^{-1}) was applied as a top-dressing in the form of limestone ammonium nitrate (LAN) (28%) five weeks after maize planting. Soil analysis indicated that potassium levels were adequate and therefore no additional potassium was

needed. Fertilizer was applied in the furrow at planting and covered with soil. Maize, Pioneer Seed cv. PHB 32D99, was hand-seeded at 44 444 seeds ha^{-1}, which represents the recommended plant density for dry-land conditions in the area (Mallett 1991).

2.3 Data collection

Data collection dates are given in Table 2. Maize data for the 2004 season were omitted, as adverse wet and rainy conditions prevented measurements being taken at designated times. Biomass samples of the cover crops were collected on each plot in four randomly placed 0.09 m^2 blocks and oven-dried at 70°C. Maize was considered to have emerged fully when the first leaf was completely unfolded. The date of final emergence was the last day emergence was measured and expressed as the percentage of seeds planted. Each plot was divided into four quarters to record the accruement of maize seedling dry weight after maize emergence. At about 14 days after emergence (DAE), 60 maize seedlings in the first quarter of each plot were cut above the soil surface and their dry weights recorded. It was repeated in the second and third plot quarters, at about 28 and 44 DAE. During 2003-2005 *C. esculentus* growth was only visually assessed but in 2006 and 2007 the leaf mass of *C. esculentus* was measured to obtain a more quantitative measurement (Table 2). Leaf material of *C. esculentus* was collected in six 0.09 m^2 blocks, in the same plot quarters used for the maize measurements. The leaf material was collected separately in inter- and intra-row maize planting lines at about 16, 28 and 41 DAE, and the dry weights determined and expressed on a per plant basis. Maize heights were measured from the soil surface to the ligule of last unfolded leaf. Harvesting was done by hand 176 DAE to determine the yield.

TABLE 2 Schedule for major field operations and measurements done on maize and *C. esculentus*

	Growing season				
Operation	**2003**	**2004**	**2005**	**2006**	**2007**
Planting of cover crops	9 Apr.	3 May	28 Apr.	31 May	14 May
Taking biomass samples	16 Oct.	12 Oct.	27 Oct.	19 Sept.	11 Oct.
Spraying cover crops	24 Oct.	14 Oct.	28 Oct.	11 Oct.	12 Oct.
Planting of maize	6 Nov.	10 Nov.	3 Nov.	23 Oct.	29 Oct.
Emergence of maize	13 Nov.		11 Nov.	29 Oct.	6 Nov.
Final maize emergence	7 DAE[1]		7 DAE	6 DAE	7 DAE
Maize seedling sampling					
1st	13 DAE		18 DAE	9 DAE	13 DAE
2nd	28 DAE		28 DAE	23 DAE	27 DAE
3rd	46 DAE		51 DAE	36 DAE	42 DAE
C. esculentus sampling					
1st				18 DAE	14 DAE
2nd				26 DAE	29 DAE
3rd				40 DAE	42 DAE
Maize height measurement	83 DAE		117 DAE	164DAE	128 DAE
Maize harvesting	166 DAE		173 DAE	169 DAE	197 DAE

1 DAE denotes days after emergence

2.4 Statistical analysis

Cover crop measurements were taken on 108 m² (18 x 6 m) plots. Maize measurements were taken on four data rows, 18 m in length and spaced 0.75 m apart. Treatments were replicated four times in a randomized block design. Data were analysed using the analysis of variance (ANOVA) procedure in the statistical package Genstat (Payne *et al.*, 2007). Treatment means were compared using Fisher's Protected Least Significant Difference procedure P=0.05. Leaf dry weight of maize seedlings, sampled at different times, was subjected to regression analysis. The non-linear relationship between dry weight and time was transformed to form a linear relationship (Gomez & Gomez 1984).

3. RESULTS

3.1. Cover crop growth

3.1.1 Climatic conditions

The mean minimum and maximum temperature data for the six-month cover crop growing period during each of the five growing seasons are shown in Figures 1 and 2.

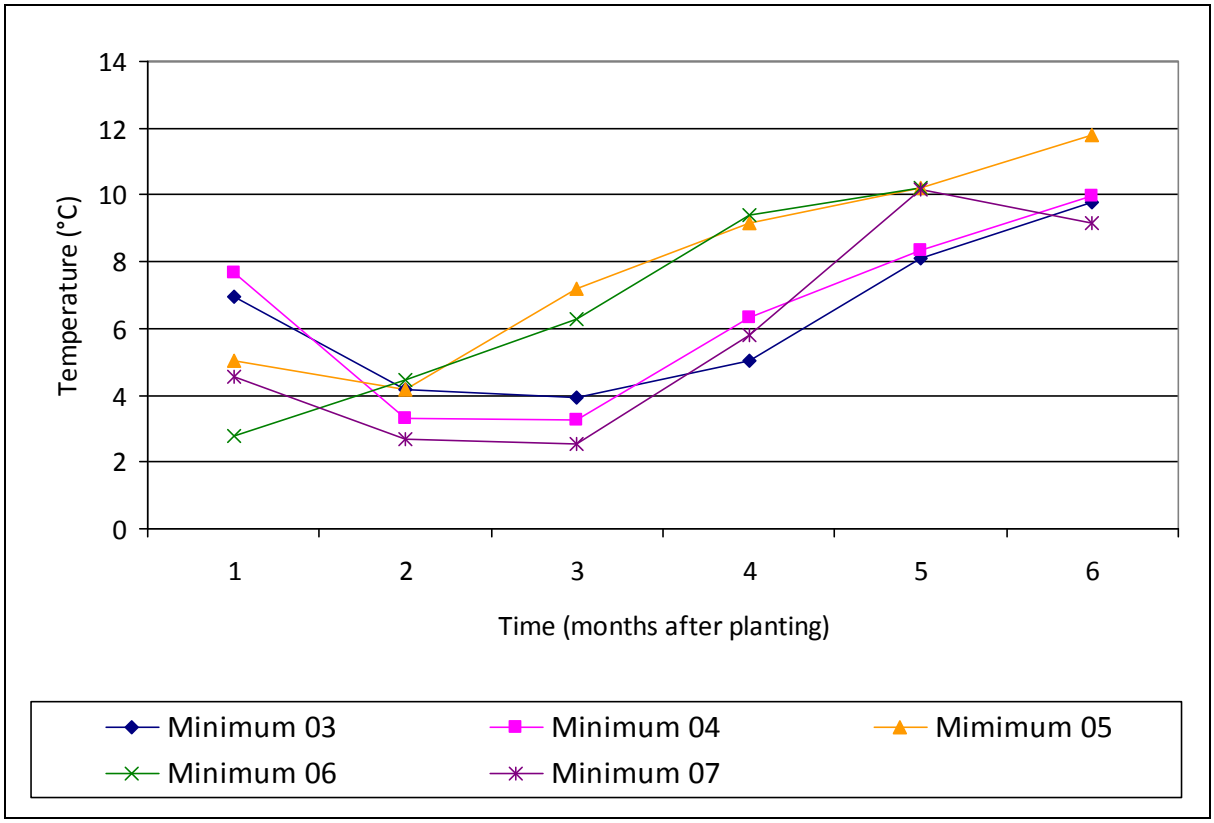

FIGURE 1 Mean minimum monthly temperatures for the six-month cover crop growth period for each of the five growing seasons

A month after planting in 2003 and 2004 the mean minimum temperatures were relatively high compared to the other seasons. Thereafter a sharp decline in temperature occurred (Figure 1). Two months after planting the mean minimum temperature in 2005 and 2006 were higher compared to the other seasons.

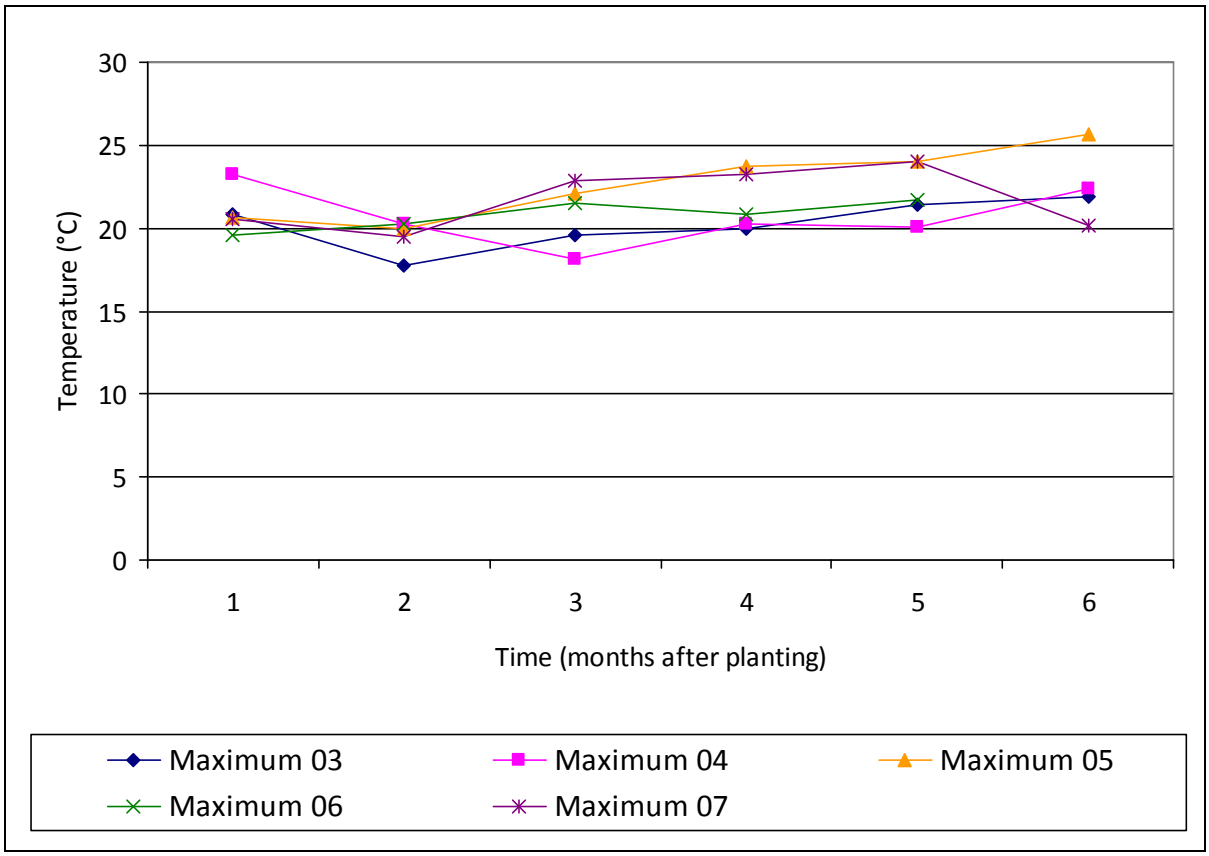

FIGURE 2 Mean maximum monthly temperatures for the six-month cover crop growth period for each of the five growing seasons

The mean maximum temperatures over the five seasons were relatively similar for the first two months after planting, except for higher temperatures in 2004, a month after planting. Two months after planting, relatively cooler conditions were experienced in 2003 and 2004 compared to the other seasons. During the last month of growth in 2007 lower temperatures were measured

The rainfall received during the six-month cover crop growth period for the five years appears in Table 3. In addition to rainfall, supplemental irrigation was supplied. Four months after the cover crop was planted, the rainfall started to increase. The highest rainfall during the growing season was received in 2003 with 229.00 mm rainfall, followed by 2007 (180.39 mm). In spite of the fact that the 2006 growing season was one month shorter, higher rainfall was received compared to the 2004 and 2005 seasons.

TABLE 3 Rainfall received during the six-month cover crop growth period for each of the five growing seasons

	Growing seasons				
	2003	**2004**	**2005**	**2006**	**2007**
Months after planting	**Rainfall received (mm)**				
1	43.00	0.40	9.00	5.20	0.20
2	6.80	20.20	1.00	0.80	33.00
3	0.20	16.00	27.39	38.39	0.00
4	33.40	12.40	16.30	32.60	12.99
5	50.60	60.59	43.40	58.99	23.20
6	95.00	6.00	16.40		111.00
Total	**229.00**	**115.59**	**110.79**	**135.98**	**180.39**

3.1.2 Cover crop yields

Growing seasons had a strong influence on the cover crop yield, as the interaction between season and treatment was highly significant (Appendix A Table 1). A decline in cover crop yields were seen from 2003 onwards, with an increase occurring in the last season (2007). In 2003, both cover crops had significantly higher yields than the weeds, while no significant yield differences between the treatments were seen in 2004–2006. In 2007, only the annual ryegrass produced significantly more biomass than the weeds. Comparison of the cover crop species with one another in each season showed no significant differences in yield.

TABLE 4 Dry matter yield of weeds and two cover crop species, annual ryegrass and stooling rye grown over five seasons (statistical analysis in Appendix A Table 1)

	Growing season					
	2003	**2004**	**2005**	**2006**	**2007**	**Mean**
Treatment	**Dry matter yield (t ha^{-1})**					
Weeds	3.45 df	8.61 b	1.98 f	2.97 ef	2.25 ef	**3.85 y**
Annual ryegrass	8.73 ab	8.69 b	3.82 df	2.08 f	5.29 cd	**5.72 x**
Stooling rye	10.82 a	6.88 bc	2.27 ef	1.73 f	4.33 de	**5.21 x**

	Treatment	**Season*Treatment**	**Means within a season**
SED	0.534	1.048	1.195
LSD	1.091	2.121	2.440
CV (%)		34.3	

[1] Means followed by the same letter are not significantly different at $P \leq 0.05$

3.2. Early maize growth

3.2.1 Climatic conditions

Different climatic conditions during the growing seasons occurred between spraying the cover crops, planting maize and 44 days after planting (DAE). Overall, 2005 and 2006 experienced warm, wet conditions, while 2003 was warmer but drier. Cool, wet conditions marked 2007. In 2003, the climatic conditions from planting to 14 DAE were characterized by hot dry conditions with most of the rain received towards the end of this period (Table 5). In contrast, in 2005, the same period was marked by warm, wet conditions with the rainfall evenly distributed during this period. In 2006 and 2007, conditions during planting to 14 DAE were marked by lower temperatures, accompanied by low rainfall in 2006 and higher rainfall in 2007. On both occasions rainfall was received towards the end of this period. During 14–44 DAE, hot dry conditions occurred in 2003 and 2006, with the rainfall evenly distributed throughout the period. In comparison, 2005 was warm but wetter, with the rainfall received throughout the period. The 2007 season was marked by cool, wet conditions, with most of the rainfall received at the beginning.

TABLE 5 Average heat units per day and total amount of rainfall received from cover crop spraying to 44 days after maize emergence

	Spraying to planting		Planting to 14 DAE[1]		14 to 44 DAE	
Season	Heat units[2] (per day)	Rainfall (mm)	Heat units (per day)	Rainfall (mm)	Heat units (per day)	Rainfall (mm)
2003	8.94	21.20	10.21	43.80	9.19	113.80
2005	10.08	58.80	8.64	59.00	8.69	166.53
2006	8.86	67.59	7.55	27.79	9.10	127.80
2007	6.53	52.80	6.93	45.40	7.50	150.80

[1] DAE denotes days after emergence

[2] Heat units are calculated using a base temperature of 10°C

Soil water measurements taken by the Sentek Diviner 2000 probe from planting to 44 DAE are shown in Table 6. Unfortunately, due to equipment failure the data for 2007 could not be recorded. Generally, the soil moisture content in the two non-residue treatments was lower compared to the residue treatments. With regards to the residue treatments, higher soil moisture levels were measured in the stooling rye treatment, followed by the weeds treatment. In spite of the low rainfall received during the planting to 14 DAE in 2006, the soil moisture content was higher than 2003, which received more rain, probably due to the lower temperature in 2006.

TABLE 6 Average volumetric soil water content in the upper 100 mm of soil measured from planting maize seedling to 44 days after emergence

	Planting to 14 DAE[1]			14 to 44 DAE		
	2003	**2005**	**2006**	**2003**	**2005**	**2006**
Treatments	**Volumetric soil content (mm)**					
Weeds	16.95	18.57	21.94	20.66	15.79	25.25
Annual ryegrass	15.42	16.95	21.08	18.75	14.94	24.67
Stooling rye	18.23	21.43	25.22	21.88	18.57	28.47
Hand-weeded	14.30	17.26	17.67	16.66	17.81	19.60
Herbicide	14.52	16.89	19.02	16.89	18.73	22.57

[1] DAE denotes days after emergence

3.2.2 Final maize emergence

The interaction between seasons and the final maize emergence percentages counted 7 DAE was not significant (Appendix A Table 2), but the main effects were (Table 7). Both cover crop species and the weed residues inhibited maize emergence more, as significantly fewer seedlings emerged in the latter than in the two non-residue treatments. No significant differences occurred between the two cover crop residue treatments. Significantly lower cover crop plant populations were measured in 2005 and 2007 compared to 2003 and 2006, with the lowest population in 2005.

TABLE 7 Influence of weeds and residues of annual ryegrass and stooling rye on the final number of maize seedlings that emerged seven days after planting (statistical analysis in Appendix A Table 2)

	Growing season				
	2003	**2005**	**2006**	**2007**	**Mean**
Treatment	**Final emergence (%)**				
Weeds	92.1	63.9	86.4	69.7	**78.0 b**
Annual ryegrass	77.5	37.2	78.4	49.4	**60.6 c**
Stooling rye	84.7	49.7	80.0	51.8	**66.5 c**
Hand-weeded	93.3	73.6	93.1	83.5	**85.9 a**
Herbicide	95.5	72.7	94.7	86.4	**87.3 a**
Mean	**88.6 a**	**59.4 c**	**86.5 a**	**68.1 b**	

	Season	**Treatment**
SED	3.81	3.66
LSD	8.30	7.35
CV (%)	13.7	

[1] Means followed by the same letter are not significantly different at $P \leq 0.05$

3.2.3 Maize seedling growth over time

The relationship between accumulated seedling dry weight and time, as influenced by the different treatments over four seasons, is shown in Figure 3. Despite different climatic conditions and significant differences in maize emergence between residue and non-residue treatments, it had little effect on the dry weight of maize seedlings 14 DAE. Thereafter, climatic conditions and the applied treatments influence growth as the seedling growth increase was higher in non-residue treatments compared to the residue treatments. Comparison of the residue treatments indicated that maize growth was more suppressed in the annual ryegrass residues than in either the stooling rye or weeds residues. The least reduction in maize growth occurred in the weeds treatment.

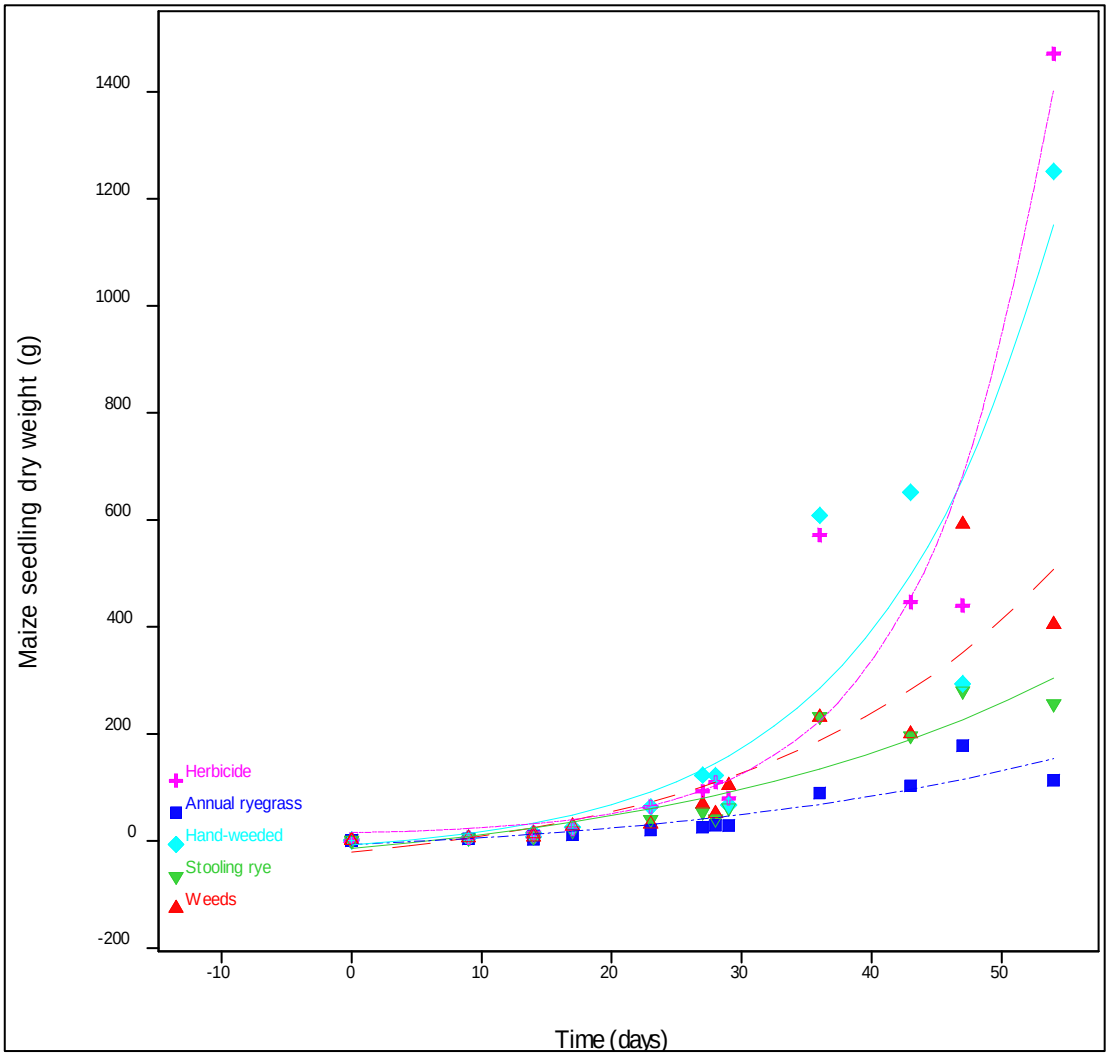

FIGURE 3 Relationship between maize seedling dry weight and time (days after emergence) as influenced by different treatments over four seasons.
Adjusted R^2=84.90.The equation for the curves are: $Y^{Weeds}=6.25+8.42e^{(0.077x)}$, $Y^{Rye}=13.73+5.06e^{(0.077x)}$, $Y^{Ryegrass}=7.83+2.54e^{(0.077x)}$, $Y^{Hand\text{-}weeded}=-18.25+18.12e^{(0.077x)}$, $Y^{Herbicide}=-44.79+20.74e^{(0.077x)}$ where Y is the dry weight of the maize seedlings (g per m^2) and X is the time after sowing. (statistical analysis in Appendix A Table 3)

The non-linear transformation of the growth curves to a linear function showed that maize seedling growth, expressed in dry weight, was positively correlated (y=0.10174x+0.292) with time (Figure 4). Maize seedlings growing in non-residue treatments had higher dry weights while maize growth was significantly inhibited by the annual ryegrass residues compared with the rest of the

treatments, except the stooling rye treatment. Differences between the weed residues and the stooling rye treatments were not significant, this despite the fact that stooling rye and annual ryegrass had relatively similar amounts of residue on the soil surface.

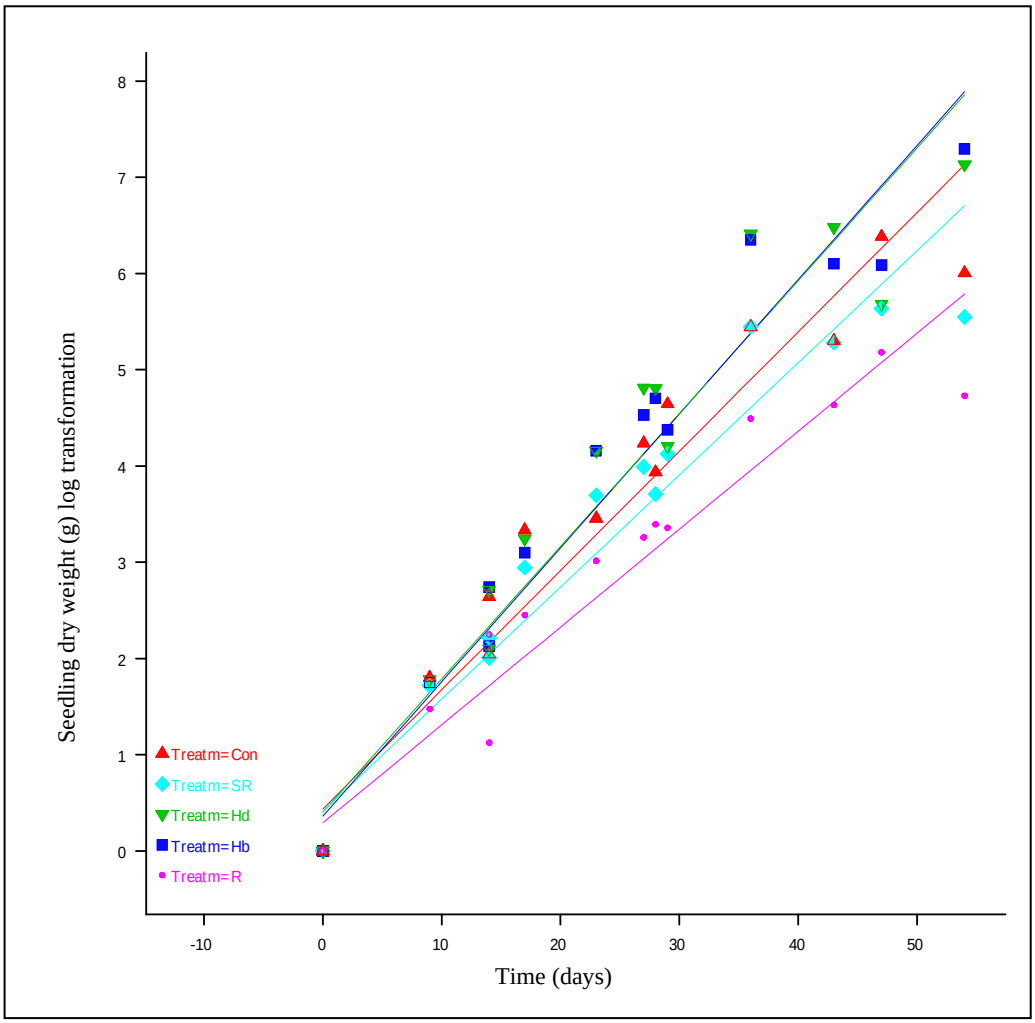

FIGURE 4 Relationship between maize seedling dry weight and time as influenced by different treatments: Con (weeds), SR (stooling rye), Hd (hand-weeded), Hb (herbicide) and R (annual ryegrass).

Adjusted R^2 = 94.2 Y = 0.10174x + 0.292 (statistical analysis in Appendix A Table 4)

3.3 C. esculentus *growth*

Due to the dominance of *C. esculentus,* leaf growth was measured separately in the intra- and inter-row maize planting lines in 2006 and 2007. High coefficient of variance (CV) characterized the statistical analysis of the dry weight data of *C.*

esculentus. Transformation of the data did not stabilize the CV or change the significance. The interaction between growing season and treatment was not significant for sampling in intra- and inter-row planting lines at 16, 28 and 41 DAE but the treatment effect was (Appendix A Tables 5–10).

Dry weight of *C. esculentus* top growth sampled in 2006 and 2007 were not significantly different, except for leaf material collected in the intra-row planting lines 16 DAE (Table 8). Although differences were not significant, more *C. esculentus* leaf material was collected in the intra-row planting lines in 2006 compared to 2007. It was only during 16 DAE that higher amounts of leaf material were collected in 2006 in the inter-row planting lines. Thereafter, more *C. esculentus* material was collected in 2007.

TABLE 8 Dry weight accruement of *C. esculentus* top growth sampled over two seasons in intra- and inter-row maize planting lines at 16, 28 and 41 days after maize emergence (statistical analysis appears in Appendix A Tables 5–10)

	Intra-row planting lines			**Inter-row planting lines**		
	Sampling period			**Sampling period**		
	16 DAE[1]	**28 DAE**	**41 DAE**	**16 DAE**	**28 DAE**	**41 DAE**
Season	**Dry weight (t ha^{-1})**			**Dry weight (t ha^{-1})**		
2006	0.99 a	1.76 a	2.87 a	0.50 a	0.83 a	1.39 a
2007	0.45 b	1.41 a	2.40 a	0.30 a	0.91 a	1.89 a

	Intra-row planting lines			**Inter-row planting lines**		
	Sampling period			**Sampling period**		
	16 DAE	**28 DAE**	**41 DAE**	**16 DAE**	**28 DAE**	**41 DAE**
SED	0.218	0.337	0.215	0.159	0.163	0.219
LSD	0.534	0.826	0.526	0.389	0.399	0.536
CV (%)	52.6	42.5	39.0	69.5	35.9	45.9

[1] DAE denotes days after emergence
[2] Means followed by the same letter within a sampling period are not significantly different at $P \leq 0.05$

Comparisons of *C. esculentus* dry weight collected in the intra-row maize planting lines, at the three sampling periods, indicated that it was only at 16 DAE, that significantly different amounts of *C. esculentus* leaf material were collected amongst the treatments (Table 9). Stooling rye residues suppressed *C. esculentus* growth significantly more than the weed residues, but the effect of the former was not significantly different from the annual ryegrass treatment. *C. esculentus* growth suppression by annual ryegrass residues was similar to that achieved by the weed residues. After 16 DAE, no significant differences were observed amongst the treatments, even though the suppression by stooling rye residues was longer lasting.

TABLE 9 Dry weight accruement of *C. esculentus* top growth sampled in the intra-row maize planting lines at 16, 28 and 41 days after maize emergence (statistical analysis appears in Appendix A Tables 5–7)

Treatment	Sampling period		
	16 DAE[1]	28 DAE	41 DAE
	Dry weight (t ha^{-1})		
Weeds	1.02 a	1.87 a	2.94 a
Annual ryegrass	0.62 ab	1.67 a	2.82 a
Stooling rye	0.53 b	1.23 a	2.14 a

	Collection period		
	16 DAE	**28 DAE**	**41 DAE**
SED	0.190	0.338	0.514
LSD	0.415	0.735	1.120
CV (%)	52.6	42.5	39.0

[1] DAE denotes days after emergence
[2] Means followed by the same letter within a sampling period are not significantly different at $P \leq 0.05$

Evaluation of the influence of the different residue types on *C. esculentus* growth that occurred in the inter-row maize planting lines showed that, during 16 and 28 DAE, the residues of both cover crop species significantly reduced *C. esculentus* growth compared to the weed residues (Table 10 and Figures 5 and 6).

At 41 DAE, only stooling rye residues significantly reduced *C. esculentus* growth, compared to the weed residues.

TABLE 10 Dry weight accruement of *C. esculentus* top growth sampled in the inter-row maize planting lines at 16, 28 and 41 days after maize emergence (statistical analysis appears in Appendix A Tables 8–10)

Treatment	Sampling period		
	16 DAE[1]	28 DAE	41 DAE
	Dry weight (t ha^{-1})		
Weeds	0.74 a	1.23 a	2.18 a
Annual ryegrass	0.17 b	0.65 b	1.54 ab
Stooling rye	0.30 b	0.74 b	1.19 b

	Collection period		
	16 DAE	**28 DAE**	**41 DAE**
SED	0.140	0.156	0.376
LSD	0.304	0.341	0.820
CV (%)	69.5	35.9	45.9

[1] DAE denotes days after emergence
[2] Means followed by the same letter within a sampling period are not significantly different at $P \leq 0.05$

FIGURE 1 *C. esculentus* growth in the (A) weed residues, (B) annual ryegrass and (C) stooling rye residues 16 days after maize emergence

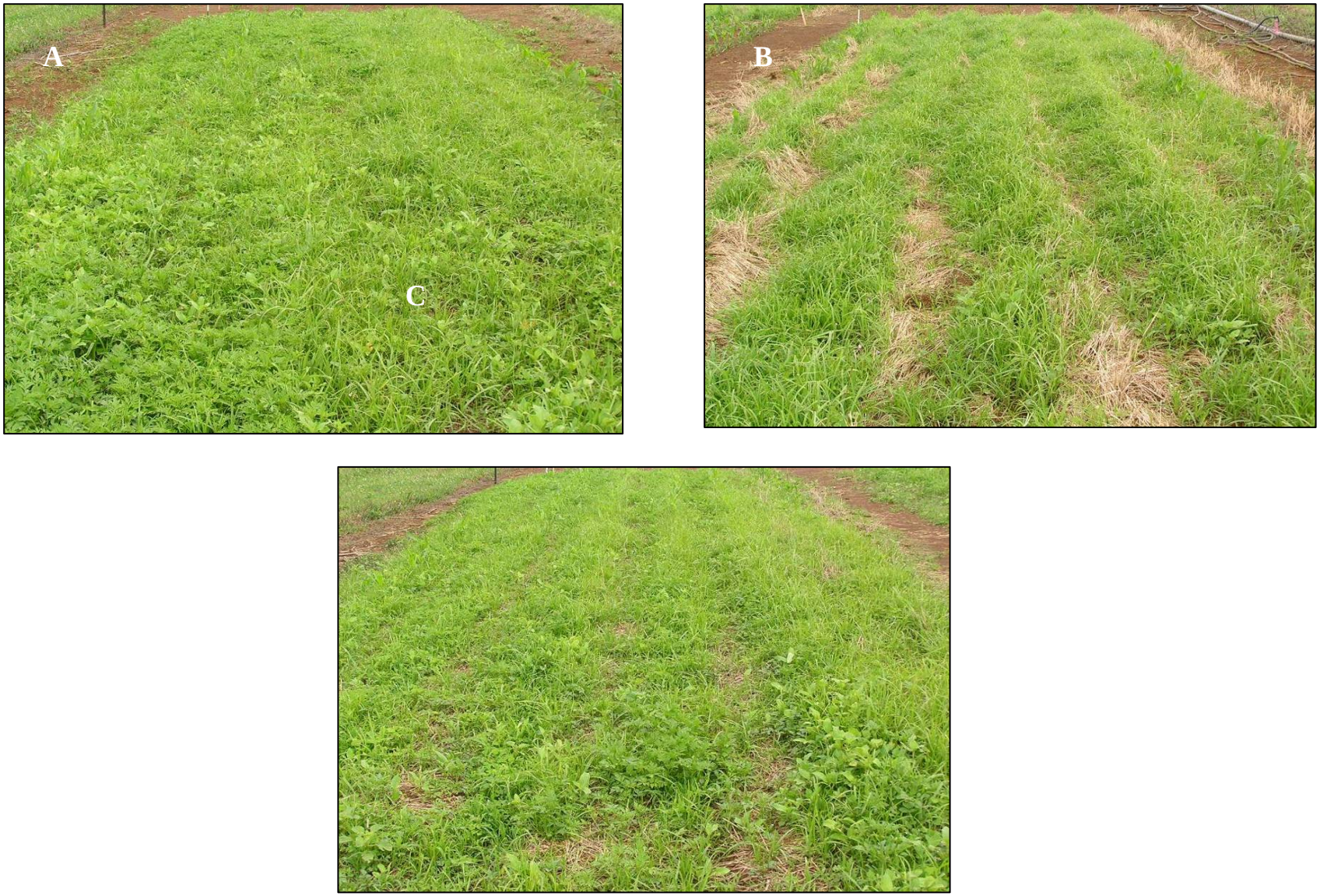

FIGURE 2 *C. esculentus* growth in the (A) weed residues, (B) annual ryegrass and (C) stooling rye residues 28 days after maize emergence

3.4 Maize height growth and yields

3.4.1 Climatic conditions

The climatic conditions over the four growing seasons from 44 days after maize emergence up to harvesting (176 DAE) are presented in Table 11. Hot conditions characterized the 2003 and 2006 seasons, main difference being that 2006 was generally drier. The 2005 and 2007 seasons were both cooler, but with more total rainfall received in 2005. The 2003 and 2005 seasons were therefore relatively more favourable for maize and *C. esculentus* growth compared to 2006 and 2007. During pollination of maize plants in January of each season, hot conditions were recorded, with the lowest rainfall received in 2006 and 2007.

TABLE 11 Climatic conditions during the growing period from 44 to 176 days after maize emergence with the rainfall and heat units for the month of January specified for each season

	Temperature		Rainfall		Heat units[1]	
	Maximum	Minimum	44–176 DAE[2]	Month of January	44–176 DAE	Month of January
Season	(°C)		(mm)		(per day)	
2003	24.91	14.13	411.00	161.20	9.52	10.27
2005	24.30	13.60	464.13	199.74	8.95	10.68
2006	26.20	14.31	336.75	74.59	10.26	11.37
2007	24.99	12.37	340.90	108.00	8.68	10.14

[1] Heat units are calculated using a base temperature of 10°C
[2] DAE denotes days after emergence

3.4.2 Maize height growth and yields

Growing seasons had a significant effect on the height and yield of maize amongst treatments (Appendix A Tables 11 and 12). During 2006 and 2007 the maize plants were taller than in 2003 and 2005, with plants being the tallest in 2006 (Table 12). Maize plants growing in the non-residue treatments were significantly taller compared to the residue treatments. Height differences

amongst maize plants in the three residue treatments were not significantly different in 2005 and 2007, but in 2003 and 2006 significantly shorter plants occurred in the annual ryegrass treatment compared to the weeds and stooling rye treatments. Over the four seasons, maize growing in the annual ryegrass residues was shorter compared to those in the other treatments. Maize growing in the weed residues was taller than those in the stooling rye residues.

TABLE 12 Height of maize measured 123 days after emergence in three residue treatments, weeds, annual ryegrass and stooling rye and two non-residue treatments (statistical analysis appears in Appendix A Table 11)

	Growing season				
	2003	**2005**	**2006**	**2007**	**Mean**
Treatment	**Height (mm)**				
Weeds	1690 a	1545 b	1768 b	1668 b	**1668 y**
Annual ryegrass	1342 b	1462 b	1404 c	1610 b	**1454 z**
Stooling rye	1545 a	1483 b	1766 b	1707 b	**1625 y**
Hand-weeded	1601 a	2036 a	2059 a	2060 a	**1939 x**
Herbicide	1721 a	2038 a	2123 a	1965 a	**1962 x**

	Treatment	**Season * Treatment**	**Means within season**
SED	53.3	138.6	106.7
LSD	107.2	281.0	214.4
CV (%)		8.7	

[1] Means followed by the same letter within a season are not significantly different at $P \leq 0.05$

Yields were significantly higher in the hand-weeded and herbicide treatments compared to the residue treatments (Table 13). Variations in yield trends occurred over the four seasons. The yields obtained in the first season, 2003, showed an anomalous trend compared to the other seasons, in that significantly different yields were measured between the annual ryegrass treatment compared to the other two treatments. Yield differences obtained in the residue treatments were not significantly different in the following three seasons. During the four

growing seasons maize in the annual ryegrass residues had the lowest yields, except in 2005.

TABLE 13 Yield of maize growing in three residue treatments, weeds, annual ryegrass and stooling rye and two non-residue treatments (statistical analysis appears in Appendix A Table 12)

	Growing season				
	2003	**2005**	**2006**	**2007**	**Mean**
Treatment	**Yield (t ha^{-1})**				
Weeds	6.31 a	2.56 b	3.11 b	2.18 b	**3.54 y**
Annual ryegrass	2.18 c	2.30 b	3.01 b	1.98 b	**2.30 z**
Stooling rye	4.20 b	2.02 b	4.76 ab	3.10 b	**3.52 y**
Hand-weeded	8.22 a	8.50 a	6.52 a	7.31 a	**7.64 x**
Herbicide	7.36 a	9.01 a	5.93 a	6.90 a	**7.30 x**

	Treatment	**Season * Treatment**	**Means within season**
SED	0.484	1.218	0.968
LSD	0.973	2.464	1.946
CV (%)		28.2	

[1] Means followed by the same letter within a season are not significantly different at $P \leq 0.05$

4. DISCUSSION

4.1 Cover crop growth

The relatively low cover crop yields in 2006 could be attributed to the shorter growing period due to a delay in planting. The highest cover crop yields were recorded in 2003. Contributing factors to the high yields likely included the early planting date, broadcasting the seed into the treatments as opposed to drilling them and the higher rainfall received, accompanied by lower temperatures thus creating favourable planting and growing conditions for cover crop growth. A decline in cover crop yields were seen from 2003 onwards, with an increase occurring in the last season (2007). The weed residues (weeds treatment) had generally lower yields than the cover crops due to the weed species present in the plots at the time of sampling. Overall, the most dominant weed species were

Fumaria muralis (fumitory), *Coronopus didymus* (carrot weed), *Oxalis* spp. (sorrel) and *Sonchus oleraceus* (sowthistle). Although these weeds covered the entire plot, they obtained lower yields compared to the two pasture species due to their unique growth characteristics. The relatively high weed yield obtained in the weeds in 2004 could have been due to more *S. oleraceus* and *Circium vulgare* (Scotch thistle) collected, while in 2005 herbicide drift from adjacent plots reduced weed growth.

4.2 Maize emergence

Despite previous reports that plant residues on the soil surface reduce crop emergence through mechanical resistance, reduced light reaching the soil surface, and interference with heat and water transfer between the soil and atmosphere (Teasdale & Mohler 2000; Teasdale *et al.,* 2007), contrasting results were obtained from the present study. As maize planting furrows were effectively devoid of residues because of the furrows being drawn with a v-shaped hoe, growth inhibition of maize could not have been due to a physical constraint contributed by the residues.

If, hypothetically, residues were present in the planting furrows, light should not have been a limitation to maize seedling emergence. Crops with big seeds seem to be less affected by the presence of residues than small seeds, because of the relatively large amount of resources available in the former (Putnam *et al.,* 1983; Teasdale 1993). Due to the relative large size of maize seeds enough resources should exist within the seed in order for coleoptiles to have emerged unimpeded through the cover crop residues in the present study. The reduction in emergence percentages in the residue treatments could not have been the result of nutrient imbalances, as the emerging seedling is totally dependent on seed reserves and thus not yet influenced by the nutrient status of the soil (Purvis 1990).

The optimum mean daily temperature for maize to germinate is between 18 and 20°C with growth being inhibited at temperatures below 10°C or above 30°C (Smith 1991). Although soil temperature was not measured in the experiment, it is possible that fluctuations in soil temperature over the four seasons could have

contributed to some of the reductions recorded for crop emergence as soil temperature could have been lower under the residue, especially with the lower air temperatures in 2005 and 2007 accompanied by higher rainfall. Kravchenko and Thelen (2007) found that the lower soil temperatures under wheat shoot and root residues decreased maize emergence more compared to plots with no wheat residues. Teasdale and Mohler (1993) suggested that a delay in germination could be expected with lower soil temperatures under cover crop residues. Differences in soil moisture were not responsible for the differential emergence, as lower soil moisture values were measured in the non-residue treatments, yet emergence was not suppressed in these treatments.

In this study it was the type of residue, rather than the amount thereof, that impaired maize seedling emergence. Burgos and Talbert (1996b) reported similar results when the number of southern pea (*Vigna unguiculata*) plants were reduced in annual ryegrass residues, despite the latter crop's residues having had a similar amount of biomass to oats and a lower amount of biomass compared to sorghum-sudangrass (*Sorghum bicolor* x *Sorghum vulgare* var. *sudanense*). Woodland species emergence was significantly reduced under grass residues compared to woodland residues (Donath & Eckstein 2008), while pasture species proved to be more restrictive to crop establishment than cereal grains (Weston 1990).

Investigating the effect of cover crop residues on crop and weed emergence revealed the involvement of putative allelochemicals with benzoxazinones and various phenolic compounds previously identified in stooling rye (Wójcik-Wojtkowiak *et al.,* 1990; Sicker *et al.,* 2004; Belz 2004). Allelochemicals are released from plants through leaching, decomposition, volatilization and root exudation (Belz 2004) and the effect is concentration dependant. The decomposition rate, leaching of water-soluble allelochemicals and the available concentration under field conditions and the prevailing temperatures, which can vary from year to year, as well as on the soil microbial activity (Purvis 1990; Facelli & Pickett 1991).

Significantly more cover crop biomass was produced in 2003 compared to 2006, yet there were no significant differences in emergence between the two seasons. After spraying the cover crops in 2003, warm and dry conditions prevailed, rendering decomposition of residues possible, but limiting the leaching of putative allelochemicals. Leaching of allelochemicals into the root zone conceivably was further reduced by the low rainfall received (29.00 mm) during the maize germination and emergence period. Similar temperatures but more rainfall occurred in 2006 during the period between killing the cover crops and maize planting making the leaching of potential allelochemicals possible. However, only 13.20 mm of rainfall fell during the emergence period, limiting the absorption of allelochemicals which could explain the similarity in emergence percentages.

Relatively similar amounts of cover crop residues were left on the soil in 2005 and 2006, but significantly more maize seedlings emerged in 2006, compared to 2005. Warm, moist climatic conditions prevailed during the decomposition period in 2005 and 2006, probably increasing the decomposition of residues and the availability of allelochemicals. Warm and dry conditions occurred during germination and emergence in 2006, which might have reduced the availability of allelochemicals and thereby reducing the possibility of a reduction in maize emergence. In contrast, conditions in 2005 were cool and moist, which could have exposed the emerging seedlings to stressful conditions and putative allelochemicals, resulting in a significant reduction in the number of seedlings that emerged.

4.3 Maize growth

In the present study, the possibility that differences in soil water content were responsible for growth differences is small, as seedlings growing in the non-residue treatments had higher dry weights compared to the residue treatments in spite of the former having generally lower soil moisture levels. The soil water moisture levels between the weeds and annual ryegrass treatments were similar, but maize seedlings were less suppressed by the weed residues than by residues

of annual ryegrass. Maize seedling growth could have been reduced by possible lower soil temperatures due to the presence of residues on the soil surface. The soil temperature under the weed residues could have possibly been higher than the cover crop residues due to the lower amount of biomass present. Both cover crop species had higher amounts of biomass present and, due to their slow decomposition residues would have been present for a longer period (Reddy 2001; Fourie *et al.,* 2001) reducing the maize growth for longer.

The residues in the current study were not incorporated and additional N was applied at planting, thereby reducing the probability that N immobilization could have suppressed growth. According to Kuo and Jellum (2002), the growth of the main crop is mainly dependant on the available N and subsequent uptake and less on the cover crop species. N mineralization is dependent on soil moisture, temperature, soil pH, the amount of available N in the soil and the C:N ratio of the residues (Kuo & Jellum 2002). The C:N ratio of cereals is mostly dependant on the time of desiccation. If killing the cover crops occurs at a late growth stage, the material would contain more carbon and the ratio could exceed 30:1, which is higher than 25:1, at which stage N immobilization would occur (Reeves 1994). In addition, N immobilization is generally greater if the residues are incorporated (Smith & Sharpley 1990). Applying N at the beginning of the growth of the main crop can reduce the initial N deficiency (Hairston *et al*., 1987; Reeves *et al*., 1990).

Another contributing factor to the difference in maize growth amongst the treatments could have been the interference from *C. esculentus* in the intra- and inter-row maize planting lines. Results from the present study, however, indicated that interference from *C. esculentus* did not have the expected impact on maize growth from planting to 14 DAE. Higher numbers of *C. esculentus* plants were sampled in the weed residue treatment compared to the cover crop treatments, yet maize seedlings had higher seedling weights in the former treatment. This is in contrast to Stoller *et al.* (1979) who found that if *C. esculentus* is not controlled from the beginning in maize production, the yield reduction can be as high as 41%, with an initial infestation of 1200 shoots m^{-2}.

Hall *et al.* (1992) stated that weed competition from the three-leaf maize growth stage reduces leaf area and expansion, thereby reducing the photosynthetic area, with a subsequent impact on growth. Reinhardt and Bezuidenhout (2001) found that maize emergence was retarded in soil where *C. esculentus* tubers were planted 28 days before planting of the crop, irrespective of whether the weeds were removed at planting. Maize emergence was not affected when the maize seeds and *C. esculentus* tubers were planted at the same time (Reinhardt & Bezuidenhout 2001).

It is possible that from 14 DAE, competition from *C. esculentus* and the presence of putative allelochemicals, both from the two cover crops and *C. esculentus,* could have been responsible for the differences in maize growth. No weed control measures were applied to the residue treatments giving rise to unlimited *C. esculentus* growth. Without adequate control, *Cyperus rotundus* (purple nutsedge) tubers increased from 0.66 tubers m^2 to 1260 tubers m^2 over two seasons increasing the competitive ability of the weed (Wang *et al.*, 2008). Morales-Payan *et al.* (2003) reported a 34% reduction in tomato shoot dry weight through interference of *C. esculentus* while soyabean yields were reduced by up to 34% from *C. esculentus* interference (Nelson & Smoot 2010). Aqueous foliage extracts of immature *C. esculentus* plants (5% m/v) and tuber extracts (2% m/v) significantly inhibited germination of lettuce (*Lactuca sativa*) seeds (Reinhardt & Bezuidenhout 2001).

4.3 C. esculentus *growth*

Over the three sampling stages employed in the present study, significantly higher numbers of *C. esculentus* material was sampled in the intra-row maize planting rows than in the inter-row lines. Reasons for this could be the sprouting of *C. esculentus* tubers after soil disturbance during maize planting and the absence of residues in the intra-row lines not presenting a physical barrier to *C. esculentus* growth. The weed residue treatment had the lowest quantity of residues on the soil surface compared to the two cover crop species. This could explain the higher *C. esculentus* dry weight measured in this treatment, both in

the intra- and inter-row planting lines, thus supporting the conclusion of Liebl *et al.* (1992) that, compared with cover crops, annual weed residues do not suppress weed growth adequately. Various authors pointed out that residues which are left on the soil surface suppress weed growth due to the physical constraint (Teasdale & Mohler 2000; Dhima *et al.,* 2006), this despite the fact that *C. esculentus* leaves have sharp tips that could penetrate hard surfaces (Stoller & Woolley 1983; Stoller & Sweet 1987). Due to its C4 photosynthesis pathway, *C. esculentus* growth could have been restricted in the inter-row maize planting lines by the limitation of light reaching the soil surface under the residues. Li *et al.* (2001) found that the number of tubers, rhizome branching and total leaf area of *C. esculentus* were reduced by shading.

Although both cover crop species had relatively similar quantities of dry matter yield, annual ryegrass residues had a profound suppression on *C. esculentus* growth 14 DAE whereafter the effect declined. It is possible that annual ryegrass residues could have prevented light from reaching the soil surface, creating a period of low light regime. Maize, hemp (*Cannabis sativa*) and barley reduced secondary shoot density, leaf biomass and tuber production of *C. esculentus* with the biggest reduction by hemp which also created a low light regime (Lotz *et al.*, 1991). Burgos and Talbert (1996b) found that residues of annual ryegrass suppressed total weed biomass by 71% compared to no cover crop and ascribe the effect to a physical interference and allelopathy. Results from work done by Breland (1996) suggest that reduced radish (*Raphanus sativus*) germination was mainly caused by phytotoxic compounds in fresh annual ryegrass residues.

In contrast, the suppression of *C. esculentus* growth by stooling rye residues was more gradual and lasted for a longer period. Comparing the cover crop residues with one another, annual ryegrass residues were denser, with a fine structure, while stooling rye was less dense and coarser. The longer suppression effect of stooling rye on *C. esculentus* growth could possibly be due to the longer decomposition period of the coarser stooling rye compared to the annual ryegrass. This is similar to results from Masiunas *et al.* (1995) and Reddy (2001) who

reported that the decomposition of stooling rye residues were slow as residues were still remaining 6–8 weeks after desiccation which could have explained why stooling rye residues suppressed *C. esculentus* growth more than annual ryegrass at 3, 6 and 9 weeks after planting soyabean. An autumn-sown rye cover crop reduced *C. esculentus* growth by 81% compared to conventional methods and Ormeño-Núñez *et al.* (2008) concluded that it was due to either the shading from the rye mulch or the possible allelochemicals released. However, both Koger *et al.* (2002) and Burgos and Talbert (1996a) reported that stooling rye residues had no suppressive effect on *C. esculentus* growth.

5. CONCLUSIONS

This study showed that both stooling rye and annual ryegrass residues suppressed *C. esculentus* establishment and density during the early growth stages of maize, possibly due to the release of putative allelochemicals from the cover crop residues. However, the influence of the cover crop residues was non-selective as it also reduced maize plant populations and fitness. This, together with competition for growth resources by *C. esculentus* later in the growing season, reduced maize height and yield. Manipulation of the cover crop killing date could influence the release of allelochemicals from the residues and alter their concentration in the root zone, thereby, either minimizing the effect on crop growth but compromise weed suppression or increase the suppression of crop and weed growth. Cover crops would have to be used in combination with chemical control methods for adequate weed suppression during the entire crop growing season due to their limited residual period. However, weed density could influence herbicide application time and method by minimizing application to planting rows only or the possibility of using only post-emergence instead of pre- and post-emergence herbicides.

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APPENDIX A Statistical analysis

TABLE 1 ANOVA for the cover crop dry matter yields over five seasons

Source of variation	DF	SS	MS	VR	F pr
Season. Block Stratum					
Season	4	364.27	91.07	31.90	<0.001
Residual (a)	15	13.18	0.88	0.31	
Season.Block.Treatment Stratum					
Treatment	2	27.37	18.68	1.28	NS
Control vs Cover crops	1	34.68	34.68	1.43	NS
Season.Treatment	8	116.69	14.59	5.11	<0.001
Season.Control vs Cover crops	4	97.25	24.31	8.52	<0.001
Residual (b)	30	85.64	2.86		
TOTAL	**59**	**617.15**			

*Residual (b) is greater than residual (a) resulting in a change in the VR values.

TABLE 2 ANOVA for the final emergence percentages of maize in the weeds and the residues of annual ryegrass and stooling rye

Source of variation	DF	SS	MS	VR	F pr
Season. Block Stratum					
Season	3	12125.90	4042.00	27.82	<0.001
Residual	12	1743.40	145.30	1.36	
Season.Block.Cover Stratum					
Cover	4	8897.50	2224.40	20.81	<0.001
Cover: Yes vs No	1	6375.40	6375.40	59.63	<0.001
Control vs Cover crops	1	2227.90	2227.90	20.84	<0.001
Stooling rye vs Ryegrass	1	277.80	277.80	2.60	0.114
Hand vs Herbicide	1	16.40	16.40	0.15	0.697
Season.Cover	12	1579.40	131.60	1.23	0.290
Season. Cover: Yes vs No	3	1084.60	361.50	3.38	0.026
Season. Control vs Cover crops	3	325.90	108.60	1.02	0.394
Season. Stooling rye vs Ryegrass	3	153.50	51.20	0.48	0.699
Season. Hand vs Herbicide	3	15.50	5.20	0.05	0.986
Residual	48	5131.70	106.90		
TOTAL	**79**	**29478.00**			

TABLE 3 Non-linear regression analysis for the of maize dry weight gain over time during four growing seasons

Source of variation	**DF**	**SS**	**MS**	**VR**	**F pr**
Regression	10	4392205	4392205	45.50	<0.001
Residual	69	666109	9654		
TOTAL	**79**	**5058314**	**64029**		
Estimates of parameter					
Parameter				**Estimate**	**SE**
Annual ryegrass				1.08	0.00724
B Treatment Weeds				8.42	
A Treatment Weeds				6.25	
B Treatment Hand				18.12	
A Treatment Hand				-18.52	
B Treatment Herbicide				20.74	
A Treatment Herbicide				-44.79	
B Treatment Stooling rye				5.06	
A Treatment Stooling rye				13.73	
B Treatment Annual ryegrass				2.54	
A Treatment Annual ryegrass				7.83	

Standard error of observations 98.3

Adjusted R^2 = 84.9

TABLE 4 Linear regression analyses for the maize dry weight gain over time during four growing seasons

Source of variation	**DF**	**SS**	**MS**	**VR**	**F pr**
Regression	9	370.02	41.11	145.04	<0.001
Residual	70	19.84	0.28		
TOTAL	**79**	**389.86**	**4.94**		
Estimates of parameter					
Parameter		**Estimate**	**SE**	**T(70)**	**F pr**
Constant		0.29	0.21	1.37	0.176
Days		0.10	0.01	13.03	<0.001
Treatment Stooling rye		0.12	0.30	0.40	0.691
Treatment Herbicide		0.07	0.30	0.23	0.816
Treatment Hand		0.11	0.30	0.37	0.713
Treatment Weeds		0.14	0.30	0.47	0.639
Days.Treatment Stooling rye		0.01	0.01	1.33	0.186
Days.Treatment Herbicide		0.04	0.01	3.41	0.001
Days.Treatment Hand		0.04	0.01	3.29	0.002
Days.Treatment Weeds		0.02	0.01	2.02	0.048

Standard error of observations 0.532

Adjusted R^2 = 94.3

TABLE 5 ANOVA for the *C. esculentus* dry weight gain in the intra-row maize planting lines at 16 days after maize emergence in the weeds, annual ryegrass and stooling rye residues

Source of variation	DF	SS	MS	VR	F pr
Season. Block Stratum					
Season	1	1.74	1.74	6.07	0.049
Residual	6	1.72	0.29	1.98	
Season.Block.Treatment Stratum					
Treatment	2	1.10	0.55	3.81	0.052
Control vs Cover crops	1	1.07	1.07	7.42	0.018
Season.Treatment	2	0.23	0.12	0.81	0.469
Season.Control vs Cover crops	1	0.23	0.23	1.61	0.228
Residual	12	1.74	0.15		
TOTAL	**23**	**6.53**			

TABLE 6 ANOVA for the *C. esculentus* dry weight gain in the intra-row maize planting lines at 28 days after maize emergence in the weeds, annual ryegrass and stooling rye residues

Source of variation	DF	SS	MS	VR	F pr
Season. Block Stratum					
Season	1	0.75	0.75	1.09	0.336
Residual	6	4.10	0.68	1.50	
Season.Block.Treatment Stratum					
Treatment	2	1.69	0.84	1.85	0.199
Control vs Cover crops	1	0.93	0.93	2.04	0.178
Season.Treatment	2	0.19	0.10	0.21	0.814
Season.Control vs Cover crops	1	0.04	0.04	0.08	0.786
Residual	12	5.47	0.46		
TOTAL	**23**	**12.19**			

TABLE 7 ANOVA for the *C. esculentus* dry weight gain in the intra-row maize planting lines at 41 days after maize emergence in the weeds, annual ryegrass and stooling rye residues

Source of variation	DF	SS	MS	VR	F pr
Season. Block Stratum					
Season	1	1.31	1.31	1.23	NS*
Residual (a)	6	1.67	0.28	0.26	
Season.Block.Treatment Stratum					
Treatment	2	3.00	1.50	1.42	0.280
Control vs Cover crops	1	1.15	1.15	1.08	0.318
Season.Treatment	2	0.04	0.02	0.02	0.981
Season.Control vs Cover crops	1	0.01	0.01	0.01	0.939
Residual (b)	12	12.69	1.06		
TOTAL	**23**	**18.71**			

*Residual (b) is greater than residual a resulting in (a) change in the VR value. Therefore it is not significant.

TABLE 8 ANOVA for the *C. esculentus* dry weight gain in the inter-row maize planting lines at 16 days after maize emergence in the weeds, annual ryegrass and stooling rye residues

Source of variation	DF	SS	MS	VR	F pr
Season. Block Stratum					
Season	1	0.24	0.24	1.60	0.253
Residual	6	0.91	0.15	1.95	
Season.Block.Treatment Stratum					
Treatment	2	1.45	0.72	9.28	0.004
Control vs Cover crops	1	1.38	1.38	17.72	0.001
Season.Treatment	2	0.37	0.19	2.39	0.134
Season.Control vs Cover crops	1	0.35	0.35	4.47	0.056
Residual	12	0.94	0.08		
TOTAL	**23**	**3.91**			

TABLE 9 ANOVA for the *C. esculentus* dry weight gain in the inter-row maize planting lines at 28 days after maize emergence in the weeds, annual ryegrass and stooling rye residues

Source of variation	DF	SS	MS	VR	F pr
Season. Block Stratum					
Season	1	0.05	0.05	0.29	0.610
Residual	6	0.96	0.16	1.63	
Season.Block.Treatment Stratum					
Treatment	2	1.57	0.79	8.05	0.006
Control vs Cover crops	1	0.55	1.55	15.88	0.002
Season.Treatment	2	0.16	0.08	0.80	0.470
Season.Control vs Cover crops	1	0.03	0.03	0.34	0.569
Residual	12	1.17	0.10		
TOTAL	**23**	**3.91**			

TABLE 10 ANOVA for the *C. esculentus* dry weight gain in the inter-row maize planting lines at 41 days after maize emergence in the weeds, annual ryegrass and stooling rye residues

Source of variation	DF	SS	MS	VR	F pr
Season. Block Stratum					
Season	1	1.51	1.51	2.67	NS*
Residual (a)	6	1.73	0.29	0.51	
Season.Block.Treatment Stratum					
Treatment	2	4.04	2.02	3.57	0.061
Control vs Cover crops	1	3.55	3.55	6.26	0.028
Season.Treatment	2	0.94	0.47	0.83	0.459
Season.Control vs Cover crops	1	0.81	0.81	1.44	0.254
Residual (b)	12	6.80	0.57		
TOTAL	**23**	**15.03**			

*Residual (b) is greater than residual a resulting in (a) change in the VR values. Therefore it is not significant.

TABLE 11 ANOVA for maize plant heights in the weeds, annual ryegrass and stooling rye residues

Source of variation	DF	SS	MS	VR	F pr
Season. Block Stratum					
Season	3	738071.00	246024.00	2.44	0.115
Residual	12	1211538.00	100961.00	4.44	
Season.Block.Cover Stratum					
Cover	4	3010147.00	752537.00	33.08	<0.001
Cover: Yes vs No	1	2598326.00	2598326.00	114.21	<0.001
Control vs Cover crops	1	174555.00	174555.00	7.67	0.008
Stooling rye vs Annual ryegrass	1	233149.00	233149.00	10.25	0.002
Hand vs Herbicide	1	4118.00	4118.00	0.18	0.672
Season.Cover	12	704655.00	58721.00	2.58	0.010
Season. Cover: Yes vs No	3	432047.00	144016.00	6.33	0.001
Season. Control vs Cover crops	3	91266.00	30422.00	1.34	0.273
Season. Stooling rye vs Ryegrass	3	130739.00	43580.00	1.92	0.140
Season. Hand vs Herbicide	3	50604.00	16868.00	0.74	0.533
Residual	48	1092049.00	22751.00		
TOTAL	**79**	**6756461.00**			

TABLE 12 ANOVA for maize yields in the weeds, annual ryegrass and stooling rye residues

Source of variation	DF	SS	MS	VR	F pr
Season. Block Stratum					
Season	3	19.75	6.58	0.90	0.471
Residual	12	88.12	7.34	3.92	
Season.Block.Cover Stratum					
Cover	4	380.12	95.03	50.73	<0.001
Cover: Yes vs No	1	363.06	363.06	193.80	<0.001
Control vs Cover crops	1	4.24	4.24	2.262	0.139
Stooling rye vs Annual ryegrass	1	11.91	11.91	6.36	0.015
Hand vs Herbicide	1	0.91	0.91	0.49	0.489
Season.Cover	12	73.10	6.09	3.25	0.002
Season. Cover: Yes vs No	3	41.59	13.86	7.40	<0.001
Season. Control vs Cover crops	3	24.49	8.16	4.36	0.009
Season. Stooling rye vs Ryegrass	3	4.91	1.64	0.87	0.461
Season. Hand vs Herbicide	3	2.12	0.71	0.38	0.770
Residual	48	89.92	1.87		
TOTAL	**79**	**651.01**			

CHAPTER 3

Influence of *Avena sativa*, *Secale cereale* and three cultivars of *Lolium multiflorum* on *Zea mays* and *Cyperus esculentus* growth under controlled conditions

CONTENTS

LIST OF TABLES AND FIGURES

CHAPTER 3

Influence of *Avena sativa*, *Secale cereale* and three cultivars of *Lolium multiflorum* on *Zea mays* and *Cyperus esculentus* growth under controlled conditions

1. INTRODUCTION

Winter cover crops play an important role in sustainable agriculture through their ability to improve soil conditions, reduce soil erosion, and suppress weed growth. Weed suppression by cover crops is achieved through modification of environmental factors and the release of allelochemicals by allelopathic plants (Teasdale *et al*., 2007). Selection of a particular cover crop species depends on the purpose for which it will be used. Different cultivars of the same cover crop differ, not only in terms of their general weed suppression abilities but also through the reduction of growth of specific weed species as well (Bordelon & Weller 1997; Vasilakoglou *et al.,* 2006).

Stooling rye (*Secale cereale*) had been considered for weed suppression because of its biomass production and apparent allelopathic potential. Stooling rye reduced weed emergence by 43–100%, depending on the weed species (Shilling *et al*., 1995). Different allelochemicals have been identified in stooling rye, including phenolic acids (Wójcik-Wojtkowiak *et al*., 1990) and benzoxazolinones (Nair *et al*., 1990). Chon & Kim (2004) reported that weed suppression by oats (*Avena sativa*) is a possibility, identifying phenolics and benzoxazolinones as inhibitors of growth. Although annual ryegrass is acknowledged as a good cover crop with regards to weed suppression (Weston 1990), limited information is available on its possible allelopathic effect.

Limitations on a standardized methodology for allelopathy research and inconclusive reports impede research efforts and information on the phenomenon. Various studies that were done in laboratories and greenhouses reported on the alleged allelopathic effect of plants without considering the influence of the growth medium and abiotic and biotic stress factors (Foy & Inderjit 2001). These

influences may be lost or modified in a controlled environment. The studies therefore only indicated the possibility of the phenomenon existing but did not prove that allelopathy is operational (Inderjit & Weston 2000). However, laboratory and greenhouse studies can generate meaningful data to understand plant behaviour that may be the result of allelopathic interactions (Inderjit & Weston 2000).

Anecdotal evidence of poor crop establishment in different annual ryegrass cultivar residues and weed suppression by oats (*Avena sativa* L.) emanating from the local farming community, plus previous research done on the suppression abilities of different cover crop species (Norsworthy *et al.,* 2007) and cultivars (Reberg-Horton *et al.,* 2009) prompted the inclusion of oats and two additional annual ryegrass cultivars to address the ability of different cover crop species and cultivars to suppress *Cyperus esculentus* (yellow nutsedge) growth and influence early maize (*Zea mays*) growth in a tunnel experiment.

2. MATERIALS AND METHODS

2.1 Experimental site

A pot experiment was carried out in 2009 in a temperature controlled plastic tunnel at the Cedara Research Station of the KwaZulu-Natal Department of Agriculture and Environmental Affairs, South Africa (latitude 29°32'S; longitude 30°16'E; altitude 1051 m). The temperature during the day (06:00–18:00) was set not to exceed 25°C, while no adjustments were made to the night-time temperature. Plastic pots (195 mm diameter, 200 mm in height) were filled with four kilograms of Umgeni sand consisting of 4.95% clay (<0.002 mm), 3.29% silt (0.002–0.05 mm) and 91.76% sand (0.05–2.00 mm). Before planting the cover crops, the sand was washed with tap water until clean water drained out of the base. Nitrogen (350 kg ha^{-1}), phosphorus (95 kg ha^{-1}) and potassium (250 kg ha^{-1}) were applied as solid NPK 2:3:4 (30%) fertilizer with 0.5% added zinc according to recommendations for annual ryegrass establishment. The balance of nitrogen (286 kg ha^{-1}) was applied at planting as limestone ammonium nitrate (LAN) (28%) and potassium (123 kg ha^{-1}) as potassium chloride (KCl) (50%). During the

growth period, water and plant samples were collected for nutrient analysis. Water draining out of the cover crop pots (= leachate) was collected in pots lined with a clear plastic bag which was then used to water the cover crops again. The nutrient solution was therefore recirculated in order to minimize nutrient variation and putative allelochemicals exuded through the roots.

2.2 Treatments

Three cover species, stooling rye cultivar 'Agri Blue', oats cultivar 'Heros' and annual ryegrass cultivars 'Agriton', 'Midmar' and 'Sophia', were planted on 11 May 2009 at 100, 70 and 30 kg ha^{-1} respectively in the pots and covered with a thin layer of sand. No treatments were applied to the cover crops during their growth period. Cover crop leaf growth was cut 100 mm above the soil surface at seven and 15 weeks after emergence (WAE). Twenty one weeks after emergence, the cover crops were killed by spraying glyphosate-isopropylamine (Roundup Turbo SL, 450 g a.i. L^{-1}, Monsanto) at a rate of 2160 g a.i. ha^{-1}, using a flat fan nozzle (Teejet XR 8002VS) at 2 kPa.

Four cover crop treatments were included in the experimental design and instituted two weeks after the cover cops were sprayed with glyphosate-isopropylamine. Treatment one (= leaf+root) consisted of dead cover crop material being left intact in the pots while in the second treatment (= roots) the cover crop leaf material was cut at the soil surface and removed, leaving the roots intact. The leaf material was weighed to obtain samples that equated to dry matter yields equivalent to 5 t ha^{-1} for stooling rye and annual ryegrass, and 4 t ha^{-1} for oats. Pots filled with previously unused sand, treated in the same manner as described for establishing the cover crops, were used in treatment three and four. For treatment three (= leaf material) the weighed leaf material was placed on top of the sand in pots while for treatment four (= soaked leaf material) the leaf material was soaked overnight (24 hours) in tap water. It was then rinsed twice with tap water before being placed on top of the sand. The control was treated in the same manner as for planting cover crops except they were not established (Figure 1).

FIGURE 7 Different cover crop residue treatments into which maize and *C. esculentus* were planted, where (A) represents the control, (B) the soaked or unsoaked leaf material and (C) the root material

Ten maize seeds (Pioneer Seeds PHB 32D99) and ten *C. esculentus* tubers were planted separately into the four treatments to a depth of 50 mm on 29 and 30 October 2009, respectively. In treatments one and two, the soil was loosened before planting the seeds and tubers by wriggling a solid plastic tube that was inserted to the required depth into the soil. Afterwards, all the pots received 500 ml tap water. This was done only at planting. Water draining out of the pots was collected in pots lined with a clear plastic bag which was then used to water the maize and *C. esculentus* plants again once a week. The nutrient solution was therefore recirculated.

Soil temperature during the emergence phase for the maize and *C. esculentus* was measured with a type T thermocouple (copper and constantan) inserted into treatments one, two, three and the control. Treatments three and four were relatively similar as the material in treatment three became soaked after the

pots were watered. Therefore, only treatment three was included. Data was recorded for six days with a Campbell Scientific Inc. CRX10® datalogger.

2.3 Data collection

Maize and *C. esculentus* were considered to have emerged when the seedlings protruded 20 mm above the soil surface. The date of final emergence was the last day emergence was measured and expressed as the percentage of seeds planted. Maize height and stem diameter measurements were taken 21 DAE (days after emergence). Height was taken from the soil surface to the ligule of the last fully expanded leaf, and stem diameter just above the soil surface. At the same time, the number of leaves was recorded by counting only fully expanded leaves where the ligule was visible. The foliage (stem and leaves) of maize and *C. esculentus* plants was sampled and oven-dried at 70°C for 48 hours to determine the dry weight. The watering solution and leaves were analysed for nutrient content after harvesting.

2.4 Statistical analysis

The pots were placed on movable trolleys which once a week were pushed to a different location in the tunnel (Figure 2). Treatments were replicated 10 times in a randomized block design, with each trolley representing a block. Data for emergence, maize height, stem diameter and dry weight were analysed using the analysis of variance (ANOVA) procedure in the statistical package Genstat (Payne *et al.*, 2007). Treatment means were compared using Fisher's Least Significant Difference procedure P=0.05.

FIGURE 8 Oats, annual ryegrass and stooling rye at six weeks after being planted into pots and placed on movable trolleys inside a plastic tunnel

2.5 Chemical analysis

Chemical analysis of the leachate collected from the root treatment of the three annual ryegrass cultivars and oats was carried out by an independent laboratory Biochemical and Scientific Consultants cc[2]. A decision was made that in the light of unforeseen financial restrictions, chemical analysis would be done only on the leachate collected from the root treatment (Treatment 2) of the three annual ryegrass cultivars and oats. Analyses on three phenolic acids, vanillic, ferulic and hydroxybenzoic acids as well as the benzoic acid benzoxazolin-2(3*H*)-one (BOA) were performed. The leachate from the root treatments were collected in the dark, 10 days after planting maize and *C. esculentus* and kept in the dark at 3°C until analysis was done.

[2] Biochemical and Scientific Consultants cc, P.O. Box 469, Hilton, 3245, South Africa, drsandybye@mweb.co.za. Tel: 033 343 1414, Fax: 033 343 1478

The qualitative analysis of the phenolic acid content was performed by means of a Waters Module 1 HPLC with UV/Vis detector, detection wavelength 220 nm, autosampler and Clarity software. Vanillic acid, supplied by Fluka Chemicals, ferulic acid and 4-hydroxybenzoic acid, both supplied by Sigma-Aldrich Chemicals, were used as standards. 11.4 mg vanillic acid, 17.6 mg ferulic acid and 16.4 mg hydoxybenzoic acid were accurately weighed out into a 50 ml volumetric flasks and each dissolved in 10ml mobile phase by ultrasonicating for five minutes. These were then made up to volume with the mobile phase which consisted of 800 ml ultra pure water, 200 ml acetonitrile and 0.25 ml trifluoroacetic acid. The standard solutions were filtered through 0.45 µm filter paper and 5 µl of each standard solution was injected separately and in duplicate. The annual ryegrass cultivar 'Midmar' solution was filtered and 20 µl was injected in duplicate with 50 µl of filtered solutions of the annual ryegrass cultivars 'Agriton' and 'Sophia' and oats. Comparisons were made by a Novelab C_{18} column (4.6 x 150 mm, 5 µm) at 0.5 ml min^{-1} flow.

The BOA analysis was performed according to the method of (Chiapusio *et al.*, 2004). Qualitative analysis was carried out by a Waters Module 1 HPLC with UV/Vis detector, detection wavelength 270 nm, autosampler and Millenium software. A 4.6 x 150 mm, 5 µm column filled with Novelab C_{18}, with 0.5 ml min^{-1} flow rate was used for the procedure; 12.5 mg BOA standard (Sigma-Aldrich Chemicals) was accurately weighed into a 100 ml volumetric flask and dissolved in 10 ml mobile phase by ultrasonicating for 5 minutes. This was then made up to volume with the mobile phase which consisted 800 ml ultra pure water, 195 ml acetonitrile and 5 ml glacial acetic acid. The mobile phase was filtered through a glass filter and ultrasonicated for 20 minutes to de-gas. The standard solution was filtered through 0.45 µm filter paper and 5 µl was injected in duplicate. Each of the annual ryegrass cultivars test solutions was filtered and 200 µl injected in duplicate while 150 µl was used for the oats solution.

The differences in injection volumes between the test samples in both chemical analyses were due to the fact that there were large peaks that were eluted before

the peaks of interest in these particular samples. These large peaks were interfering with the peaks of interest at the higher injection volumes, but the chromatogram showed better resolution at the lower injection volumes displaying more accurate results.

3. RESULTS

3.1 Nutrient analysis

3.1.1 Cover crop growth period

Nutrient analyses of the cover crop leaf material and leachate collected during the 21 week growth period are given in Tables 1 and 2. Due to the low sulphur content measured at seven WAE (weeks after emergence), an adjustment was made by the addition of ammonium sulphate. At 15 WAE, the nitrogen, phosphorus and potassium content were lower than at seven WAE but the analysis indicated that the nutrient content was still adequate for cover crop and subsequent maize growth.

TABLE 14 Nutrient content of oats, stooling rye and three cultivars of annual ryegrass leaf material collected at seven and 15 weeks after emergence

Treatment	Nutrient content										
	Ca	Mg	N	P	K	S	Na	Zn	Cu	Fe	Al
	(%)							(mg kg^{-1})			
	7 WAE[1]										
Oats	0.36	0.25	4.66	0.47	3.84	0.19	1005.0	46	20.6	224	131
Stooling rye	0.58	0.28	4.93	0.54	4.71	0.21	422.3	68	28.9	310	205
Annual ryegrass											
cv. 'Agriton'	0.49	0.31	5.48	0.51	5.25	0.19	644.8	36	13.4	139	71
cv. 'Midmar'	0.45	0.32	5.31	0.53	5.79	0.21	884.9	26	11.0	360	58
cv. 'Sophia'	0.49	0.33	4.91	0.45	5.16	0.19	645.0	38	8.9	242	48
	15 WAE										
Oats	0.74	0.40	3.15	0.27	2.56	1.10	241.2	20	3.2	78	34
Stooling rye	0.40	0.41	3.33	0.24	2.54	1.40	885.1	20	3.2	93	32
Annual ryegrass											
cv. 'Agriton'	1.08	0.59	3.42	0.28	3.46	2.21	986.5	32	4.6	123	44
cv. 'Midmar'	1.03	0.57	3.86	0.26	3.96	2.08	1214.0	30	4.2	121	45
cv. 'Sophia'	0.86	0.47	3.60	0.28	3.41	1.88	790.4	30	4.7	116	32

[1] WAE denotes weeks after emergence

Leachate analysis at seven WAE indicated high chloride content possibly due to the build-up of chloride in the pots (Table 2). More water was given to the cover crops from seven WAE because of increased growth which contributed to leaching of chloride from the system. Although nutrient content was lower at 15 WAE, it was still sufficient for maize growth (Thibaud, personal communication).[3]

[3] G. R. Thibaud, DAEARD, Private Bag X9059, PMB, 3200

TABLE 15 Nutrient content of the water solution (=leachate) collected from pots in which oats, stooling rye and annual ryegrass grew at seven and 15 weeks after emergence

	Cations				Anions		EC	pH	SAR
	Na	Ca	Mg	K	Alkalinity	Cl			
Treatment		(me L^{-1})			(me L^{-1})		(mS m^{-1})	(KCl)	
					7 WAE[1]				
Oats	1.17	5.05	3.07	0.13	0.96	9.5	111.1	6.42	0.58
Stooling rye	1.27	11.39	7.91	0.13	1.75	33.8	363.4	6.30	0.41
Annual ryegrass	5.09	15.25	8.23	0.7	1.02	20.8	234	6.39	1.49
					15 WAE				
Oats	0.60	2.04	0.45	0.02	0.74	0.9	31.05	6.15	0.05
Stooling rye	0.18	2.47	0.79	0.04	0.64	1.5	42.6	6.13	0.14
Annual ryegrass	0.06	1.98	0.67	0.02	0.46	0.8	33.37	5.72	0.05

[1] WAE denotes weeks after emergence

3.1.2 Maize and C. esculentus growth period

Leaf and water analyses were carried out 21 days after maize and *C. esculentus* emergence and the results appear in Tables 3 and 4. Leaf analysis of the maize seedlings growing in the different cover crop residue treatments indicated that no nutrient deficiencies occurred that could have a negative impact on maize growth (Buys 1991; James 2009). Leaf analysis was not done on *C. esculentus* as no benchmark is available for comparison. Analysis of the leachate showed that adequate nutrients were available for growth (Thibaud, personal communication)[4] despite the generally low values in the root treatment.

[4] G.R. Thibaud, DAEARD, Private Bag X9059, PMB, 3200

TABLE 16 Leaf nutrient content of maize seedlings growing in different cover crop residue treatments 21 days after emergence

Treatment	Nutrient content										
	Ca	Mg	N	P	K	S	Na	Zn	Cu	Fe	Mn
	(%)							(mg kg^{-1})			
Control	0.44	0.27	3.84	0.41	5.84	0.27	1002.6	53	5.6	432	110
Leaf+root											
Oats	0.71	0.46	3.44	0.37	3.83	0.45	606.7	33	4.1	235	272
Stooling rye	0.68	0.52	3.97	0.48	4.89	0.91	716.0	36	3.8	174	329
Annual ryegrass											
cv. 'Agriton'	0.46	0.36	3.32	0.34	4.45	0.53	795.9	28	2.1	109	211
cv. 'Midmar'	0.60	0.47	3.91	0.49	4.76	0.61	594.1	36	3.5	201	339
cv. 'Sophia'	0.49	0.39	3.95	0.39	4.42	0.81	491.7	30	4.1	126	303
Roots											
Oats	1.00	0.61	4.65	0.33	2.21	0.92	480.6	30	5.2	174	284
Stooling rye	0.69	0.49	4.41	0.36	3.28	0.73	676.7	33	5.2	205	356
Annual ryegrass											
cv. 'Agriton'	0.66	0.44	4.15	0.37	3.79	0.62	234.4	32	4.0	153	475
cv. 'Midmar'	0.75	0.51	4.19	0.53	3.99	0.67	380.2	36	4.2	186	483
cv. 'Sophia'	0.68	0.47	4.29	0.30	3.28	0.76	323.4	27	3.5	182	499
Leaf material											
Oats	0.48	0.31	3.68	0.75	5.89	0.31	874.1	31	5.4	112	128
Stooling rye	0.41	0.26	3.85	0.75	6.13	0.30	957.0	42	5.2	109	117
Annual ryegrass											
cv. 'Agriton'	0.50	0.28	4.00	0.61	6.21	0.31	363.3	45	4.1	156	126
cv. 'Midmar'	0.62	0.31	4.28	1.06	6.50	0.38	679.5	55	5.9	151	164
cv. 'Sophia'	0.44	0.29	2.69	0.45	5.29	0.25	466.8	39	3.6	113	117
Soaked leaf material											
Oats	0.43	0.31	3.12	0.47	5.25	0.24	632.0	33	3.7	102	107
Stooling rye	0.40	0.29	3.02	0.40	4.97	0.24	657.0	23	4.1	110	105
Annual ryegrass											
cv. 'Agriton'	0.39	0.26	3.19	0.40	5.74	0.24	274.4	38	3.8	139	101
cv. 'Midmar'	0.46	0.30	3.61	0.58	5.85	0.28	664.6	33	6.0	177	122
cv. 'Sophia'	0.36	0.28	2.60	0.38	4.89	0.21	613.8	28	3.3	82	89

TABLE 17 Nutrient content of leachate collected from different cover crop residue treatments in which maize seedlings were growing in 21 days after emergence

	Cations				Anions		EC	pH
	Na	Ca	Mg	K	Alkalinity	Cl		
Treatment				(me L^{-1})			(mS m^{-1})	(KCl)
Control	2.8	5.7	4.2	2.8	0.6	11.8	219.7	6.7
Leaf+root								
Oats	1.1	8.7	3.7	0.3	0.2	5.5	181.7	4.1
Stooling rye	1.4	7.3	3.4	0.8	0.3	3.1	139.6	5.6
Annual ryegrass								
cv. 'Agriton'	1.7	5.3	3.1	0.7	0.5	6.9	118.1	6.1
cv. 'Midmar'	2.3	9.6	5.5	0.8	0.4	6.5	221.4	5.2
cv. 'Sophia'	1.5	6.8	3.0	0.5	0.3	3.0	161.6	4.0
Roots								
Oats	1.1	6.4	2.6	0.1	0.2	1.0	133.4	3.6
Stooling rye	1.1	2.2	1.4	0.3	0.4	1.3	71.30	6.2
Annual ryegrass								
cv. 'Agriton'	1.6	2.6	1.5	0.3	0.5	1.0	75.9	5.8
cv. 'Midmar'	1.1	2.4	1.5	0.2	0.3	1.3	59.30	5.7
cv. 'Sophia'	1.2	2.8	1.7	0.2	0.2	1.1	84.60	3.9
Leaf material								
Oats	2.6	3.1	2.8	1.7	0.5	6.4	119.7	5.7
Stooling rye	2.4	4.7	3.8	1.0	0.4	7.8	163.9	6.2
Annual ryegrass								
cv. 'Agriton'	1.5	4.3	3.5	0.8	0.5	7.1	152.0	6.3
cv. 'Midmar'	2.6	6.9	6.5	1.5	0.4	11.5	253.3	5.8
cv. 'Sophia'	2.3	6.7	5.1	3.8	0.4	9.2	198.9	5.1
Soaked leaf material								
Oats	1.9	1.9	1.2	0.2	0.5	3.6	66.6	5.7
Stooling rye	1.1	3.4	2.9	1.8	1.0	8.4	139.4	6.4
Annual ryegrass								
cv. 'Agriton'	2.7	2.3	2.1	1.7	0.7	6.8	115.0	6.3
cv. 'Midmar'	1.9	2.9	2.5	2.0	0.7	5.4	109.2	6.3

cv. 'Sophia'	2.3	1.8	1.3	0.6	0.61	4.1	67.7	5.6

3.2 Soil temperature

Soil temperatures were measured for six days after maize and *C. esculentus* emergence and are shown in Table 5. Similar temperatures were measured in the leaf+root and leaf material treatments with residues placed on top of the soil surface. The higher ambient temperatures measured in the tunnels on 8 and 9 November 2009 could possibly be responsible for the higher soil temperatures recorded on 9 and 10 November 2009.

TABLE 18 Soil temperatures measured with a type T thermocouple during maize and *C. esculentus* emergence in the different cover crop residue treatments

	Soil temperature (°C)						
Treatment	**6 Nov**	**7 Nov**	**8 Nov**	**9 Nov**	**10 Nov**	**11 Nov**	**Mean**
Control	8.40	8.83	8.84	12.64	12.20	9.50	**10.07**
Leaf+root	8.49	9.32	8.32	13.40	12.49	9.94	**10.32**
Roots	7.88	8.44	8.09	12.43	11.68	9.30	**9.64**
Leaf material	8.56	9.35	8.49	13.07	12.58	10.16	**10.37**

3.3 Final emergence

The interaction between the cover crop residue type and species did not influence maize and *C. esculentus* emergence significantly, only the main effect of cover crop residue type (Appendix B, Tables 1 and 2). Maize seedling emergence in the leaf+root treatment was significantly inhibited compared to the control but not compared to the other residue treatments (Table 6). Final emergence percentages amongst the roots and two leaf material treatments were not significantly different. *C. esculentus* emergence was significantly inhibited in the leaf+root and roots treatments compared to the control and two leaf material treatments. No significant differences were measured amongst the two leaf material and control treatments.

TABLE 19 Influence of different cover crop residues on the final number of maize and *C. esculentus* seedlings that emerged five and seven days after planting (statistical analysis in Appendix B Tables 1 and 2)

Treatment	Maize	*Cyperus esculentus*
	Final emergence (%)	
Control	96.00 a	50.00 a
Leaf+root	88.45 b	9.60 c
Roots	94.41 ab	20.60 b
Leaf material	93.65 ab	39.00 a
Soaked leaf material	95.05 ab	47.40 a

	Maize	*C. esculentus*
	Treatment	
SED	2.92	5.46
LSD	7.45	10.76
CV. (%)	9.1	52.2

[1] Means followed by the same letter are not significantly different at $P \leq 0.05$
[2] Means are compared for test species separately

3.4 Growth parameters

3.4.1 Maize height growth

The interaction between the different cover crops species and the residue treatments was significant 21 DAE (Appendix B Table 3). Maize seedlings growing in the control treatment were significantly taller compared to the other treatments, except the soaked leaf material treatment (Table 7 and Figures 3–7). Height growth was less reduced in the leaf material treatment compared to the leaf+root and roots treatments. Maize seedlings growing in the root material of the different cover crops were the shortest while those in the soaked leaf material the tallest.

No significant maize height growth inhibition between the different annual ryegrass cultivars was observed in the leaf+root treatment. Height growth was significantly reduced by the root material of the ryegrass cultivar 'Midmar'

compared to the other cover crop species in the same treatment. No significant height growth difference amongst the different residue treatments were measured in the soaked leaf material.

Maize seedlings growing in the leaf+root and roots treatments of oats and stooling rye had relatively similar heights but was significantly shorter compared to the two leaf material treatments of the same cover crop species. The height growth was relatively similar in the leaf+root and leaf material treatments of the annual ryegrass cultivars 'Agriton' and 'Midmar'. Both was significantly taller compared to maize in the roots treatment of the two same cover crops. The maize growing in the soaked leaf material was significantly taller compared to the other residue treatments of the same cover crop species.

TABLE 20 Influence of three cover crop species residues on maize height growth 21 days after emergence (statistical analysis in Appendix B, Table 3)

	Cover crop species				
	Oats	**Stooling rye**	**Annual ryegrass**		
			'Agriton'	**'Midmar'**	**'Sophia'**
Treatment	**Height growth (mm)**				
Control			103.64 a		
Leaf+root	40.34 fg	42.34 efg	53.09 de	44.73 ef	48.39 def
Roots	43.85 efg	41.23 fg	33.57 g	28.05 h	46.80 def
Leaf material	73.86 b	65.26 bc	46.74 ef	41.79 fg	57.82 cd
Soaked leaf material	99.13 a	101.25 a	97.58 a	93.73 a	100.86 a

	Species*Treatment
SED	5.8
LSD	11.01
CV. (%)	20.1

[1] Means followed by the same letter are not significantly different at $P \leq 0.05$

3.4.2 Maize diameter growth

The interaction amongst the different cover crops species and the residue treatments was significant 21 DAE (Appendix B Table 4). The influence of the residue treatments on height growth did not always translate into the same effect on diameter growth (Table 8). The maize plants growing in the soaked leaf and leaf material had relatively similar diameters compared to the control while significantly smaller diameters were measured in the leaf+root and roots treatments.

The stem diameter of maize seedlings was the widest in leaf+root and roots treatments of the annual ryegrass 'Midmar' compared to the other cover crops in the same treatments. Variation in diameter growth was observed in the leaf material treatment with significant smaller diameters in the annual ryegrass cultivars 'Agriton' and 'Midmar' compared to the other cover crop residues. In the soaked leaf material treatment, maize seedlings growing through the oats and annual ryegrass cultivar 'Sophia' residues had significantly wider diameters compared to the other cover crop species as well as the control. Diameters were similar in the soaked leaf and leaf material treatments of oats and stooling rye. In all the annual ryegrass cultivars maize seedlings in the soaked leaf material had significantly wider diameters compared to the leaf material treatment.

TABLE 21 Influence of three cover crop species residues on maize diameter growth 21 day after emergence (statistical analysis in Appendix B, Table 4)

	Cover crop species				
	Oats	Stooling rye	Annual ryegrass		
			'Agriton'	'Midmar'	'Sophia'
Treatment	**Diameter growth (mm)**				
Control	0.68 c				
Leaf+root	0.24 g	0.25 g	0.27 fg	0.34 ef	0.25 g
Roots	0.29 efg	0.26 g	0.26 g	0.36 e	0.31 efg
Leaf material	0.78 a	0.64 c	0.52 d	0.49 d	0.66 c
Soaked leaf material	0.77 a	0.67 c	0.69 c	0.64 c	0.76 ab

	Species*Treatment
SED	0.0386
LSD	0.761
CV. (%)	17.9

[1] Means followed by the same letter are not significantly different at $P \leq 0.05$

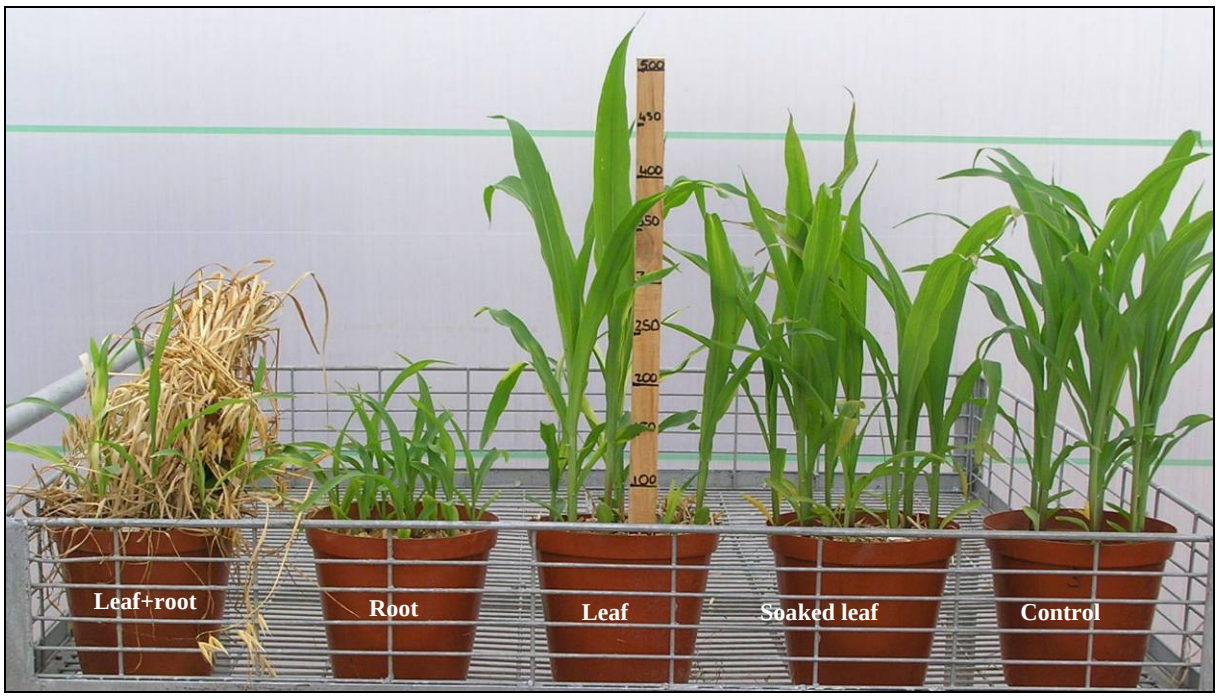

FIGURE 9 Influence of different oats residue treatments on maize growth 21 days after emergence

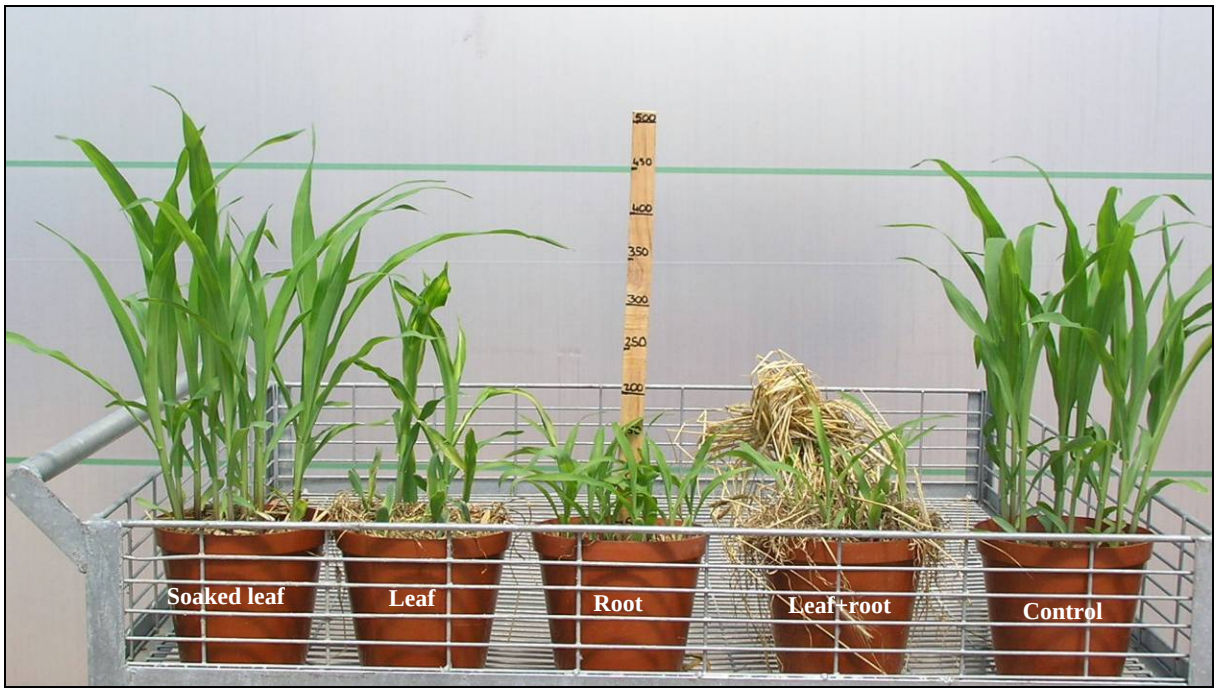

FIGURE 10 Influence of different stooling rye residue treatments on maize growth 21 days after emergence

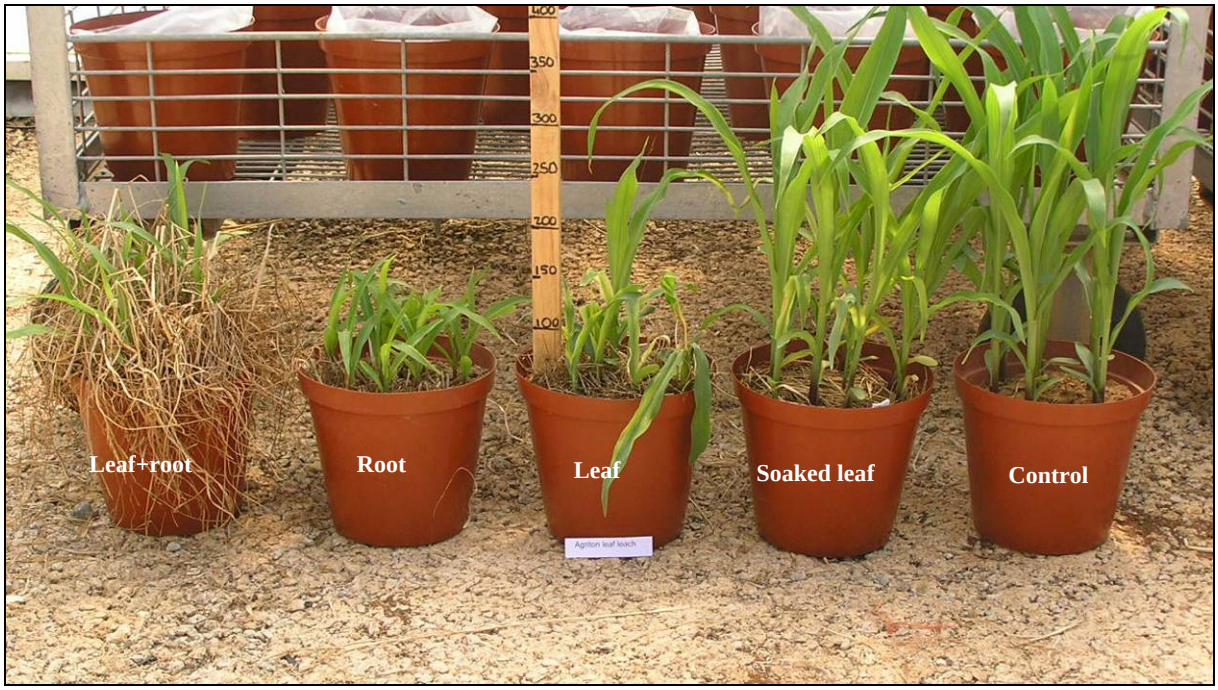

FIGURE 11 Influence of different annual ryegrass cv. 'Agriton' residue treatments on maize growth 21 days after emergence

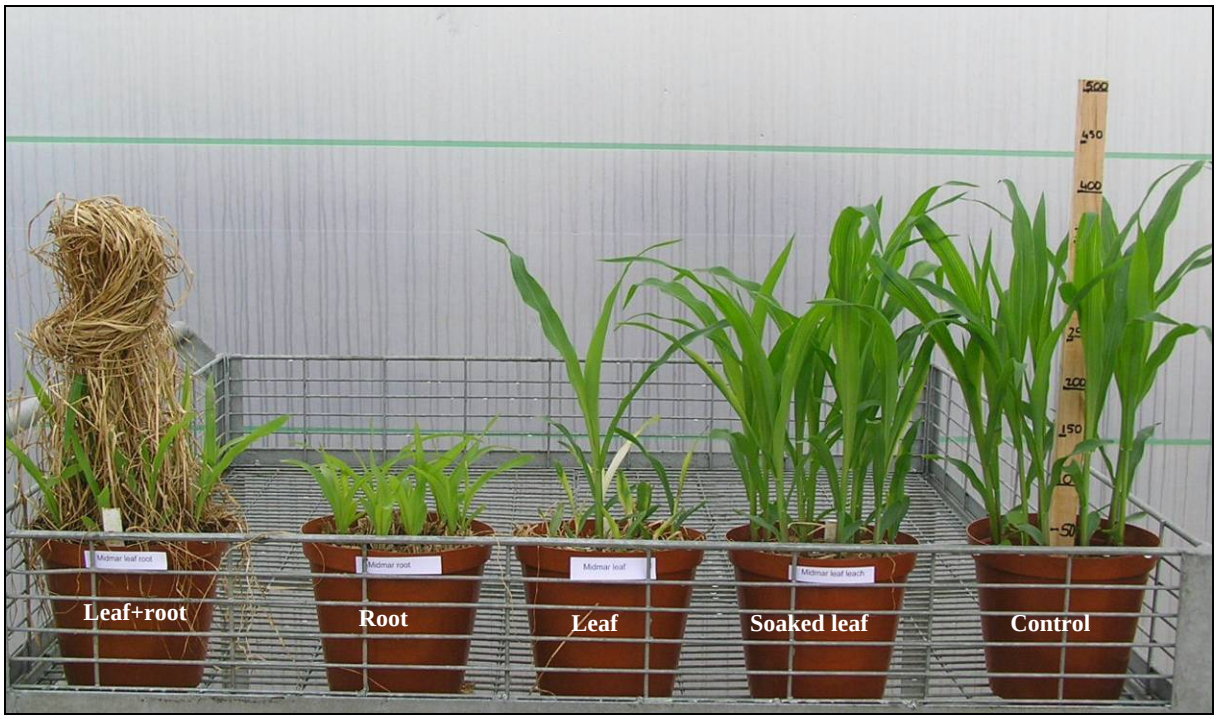

FIGURE 12 Influence of different annual ryegrass cv. 'Midmar' residue treatments on maize growth 21 days after emergence

FIGURE 13 Influence of different annual ryegrass cv. 'Sophia' residue treatments on maize growth 21 days after emergence

3.4.3 Number of fully expanded maize leaves

The interaction amongst the different cover crops species and the residue treatments was significant 21 DAE (Appendix B Table 5). Seedlings in the soaked leaf material and roots treatments had a relatively similar number of expanded leaves as the control (Table 9). Fewer leaves were counted in the leaf+root and leaf material treatments compared to the control.

Small variations in the number of leaves amongst the different cover crop species in each residue treatment occurred with the most variation amongst cover crop species in the leaf material treatment. Maize seedlings growing in the leaf+root residues of the annual ryegrass cultivar 'Agriton' had significantly more expanded leaves compared to the other cover crop species in the same treatment, except the annual ryegrass cultivar 'Sophia'. The root and leaf material of the ryegrass cultivar 'Midmar' suppressed maize leaf growth significantly more than the other cover crop species in the same two treatments. No significant differences occurred amongst the cover crop species in the soaked leaf material treatment.

The seedlings in the oats residue treatments had a similar number of expanded leaves, except in the leaf+root treatment where fewer leaves were counted. In both the stooling rye and annual ryegrass cultivar 'Sophia' the roots and soaked leaf material treatments had a relatively similar number of leaves and significantly more than the other two treatments. With regards to the annual ryegrass cultivars 'Agriton' and 'Midmar', significantly more leaves were counted in the soaked leaf material treatment compared to the roots treatment with both having significantly more expanded leaves than the leaf+root and leaf material treatments.

TABLE 22 Influence of three cover crop species residues on the number of fully expanded maize leaves 21 days after emergence (statistical analysis in Appendix B, Table 5)

	Cover crop species				
	Oats	**Stooling rye**	**Annual ryegrass**		
			'Agriton'	**'Midmar'**	**'Sophia'**
Treatment	**Number of leaves**				
Control	2.99 ab				
Leaf+root	1.70 hi	1.54 i	2.08 g	1.63 hi	1.89 gh
Roots	2.87 abc	2.79 abc	2.63 cde	2.14 fg	2.89 abc
Leaf material	2.70 bcd	2.45 de	2.06 g	1.73 hi	2.39 ef
Soaked leaf material	2.99 ab	3.01 a	3.01 a	3.00 a	3.06 a

	Species*Treatment
SED	0.145
LSD	0.286
CV. (%)	13.2

[1] Means followed by the same letter are not significantly different at $P \leq 0.05$

3.4.4 Dry weight of maize seedlings

The interaction between the cover crops species and the different residue treatments was significant 21 DAE (Appendix B Table 6). Growth, as measured by the dry weight of the seedlings, was severely inhibited by the leaf+root and roots treatments of all the cover crop species (Table 10). Growth in the soaked leaf material was generally significantly better compared to control and leaf material treatment. Although the leaf material suppressed growth compared to the soaked leaf material, it was relatively similar to the control.

No significant differences in growth were measured amongst the different cover crop species in the leaf+root and roots treatments. The leaf material of the annual ryegrass cultivars 'Agriton' and 'Midmar' were more suppressive towards maize growth than the other cover crop species in the same treatment. Growth

was suppressed by the soaked leaf material of the ryegrass cultivar 'Midmar' when compared to the other cover crop species in the same treatment, but it was not significantly suppressive compared to the control.

Overall, seedlings grew better in the soaked leaf material of the cover crops followed by the leaf material and then the root and leaf+root material.

TABLE 23 Influence of three cover crop species residues on maize dry weight 21 days after emergence (statistical analysis in Appendix B, Table 6)

	Cover crop species				
	Oats	**Stooling rye**	**Annual ryegrass**		
			'Agriton'	**'Midmar'**	**'Sophia'**
Treatment	**Dry weight per plant (g)**				
Control	0.60 c				
Leaf+root	0.07 f	0.09 f	0.10 f	0.08 f	0.08 f
Roots	0.11 ef	0.13 ef	0.09 f	0.09 f	0.13 ef
Leaf material	0.62 c	0.53 c	0.28 d	0.22 de	0.56 c
Soaked leaf material	0.81 b	0.84 ab	0.86 ab	0.60 c	0.94 a

	Species*Treatment
SED	0.058
LSD	0.114
CV. (%)	34.6

[1] Means followed by the same letter are not significantly different at $P \leq 0.05$

3.4.5 Dry weight of C. esculentus seedlings

The type of cover crop species and residual treatment significantly influenced the dry weight of *C. esculentus* seedlings 21 DAE (Appendix B, Table 7). The dry weight of *C. esculentus* seedlings in the soaked leaf material and control treatments was relatively similar (Table 11 and Figures 8–12). *C. esculentus* growth was severely inhibited in the leaf+root and roots treatments while the dry weight in the leaf material treatment was less than the control.

No significant differences in dry weight were observed amongst the different cover crop species in the leaf+root and roots treatments. In the leaf material treatment, the three annual ryegrass cultivars significantly inhibited growth compared to the oats and stooling rye. Regardless of the overnight soaking of the leaf material of the ryegrass cultivar 'Midmar', *C. esculentus* growth was still significantly inhibited compared to the soaked leaf material of the other cover crops.

As was the case with maize, *C. esculentus* grew better in the soaked leaf material of the cover crops followed by the leaf material and then the root and leaf+root material.

TABLE 24 Influence of three cover crop species residue on *C. esculentus* dry weight 21 days after emergence (statistical analysis in Appendix B, Table 7)

	Cover crop species				
	Oats	**Stooling rye**	**Annual ryegrass**		
			'Agriton'	**'Midmar'**	**'Sophia'**
Treatment	**Dry weight per plant (g)**				
Control			0.22 cd		
Leaf+root	0.02 g	0.02 g	0.03 fg	0.01 g	0.02 g
Roots	0.03 fg	0.03 fg	0.02 g	0.02 g	0.03 fg
Leaf material	0.16 e	0.14 e	0.08 f	0.08 f	0.06 fg
Soaked leaf material	0.31 ab	0.26 bc	0.25 c	0.18 de	0.33 a

	Species*Treatment
SED	0.0286
LSD	0.0564
CV. (%)	58.3

[1] Means followed by the same letter are not significantly different at $P \leq 0.05$

FIGURE 14 Influence of different oats residue treatments on *C. esculentus* growth 21 days after emergence

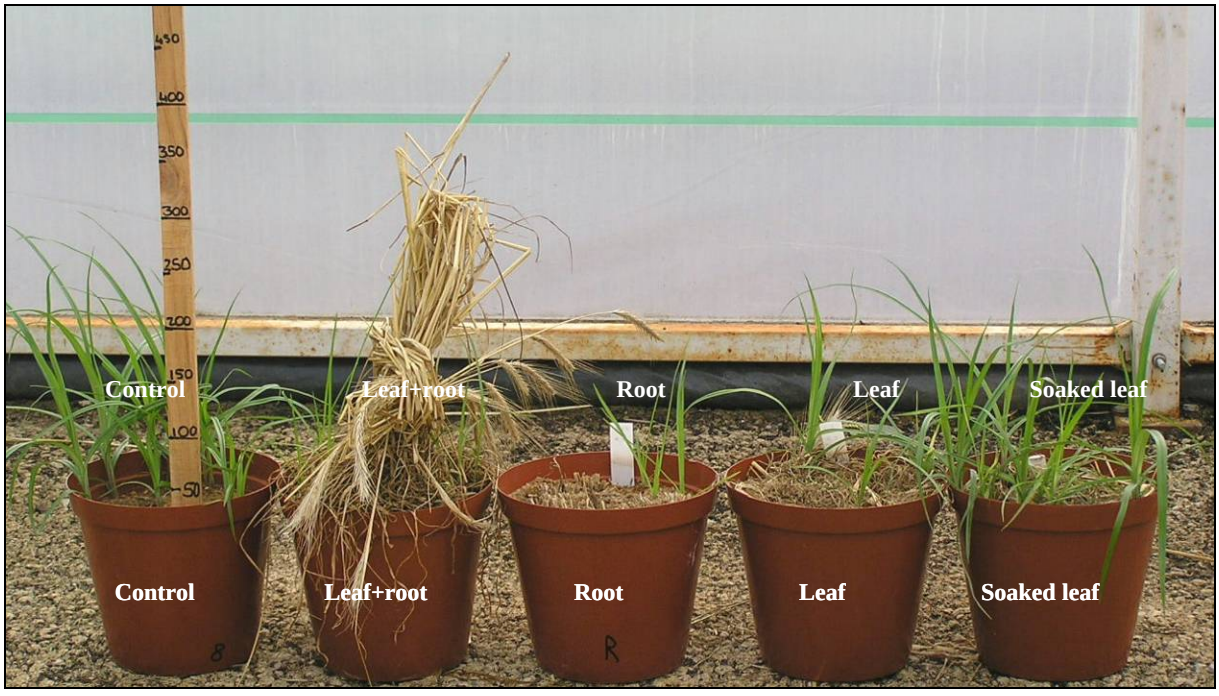

FIGURE 15 Influence of different stooling rye residue treatments on *C. esculentus* growth 21 days after emergence

FIGURE 16 Influence of different annual ryegrass cv. 'Agriton' residue treatments on *C. esculentus* growth 21 days after emergence

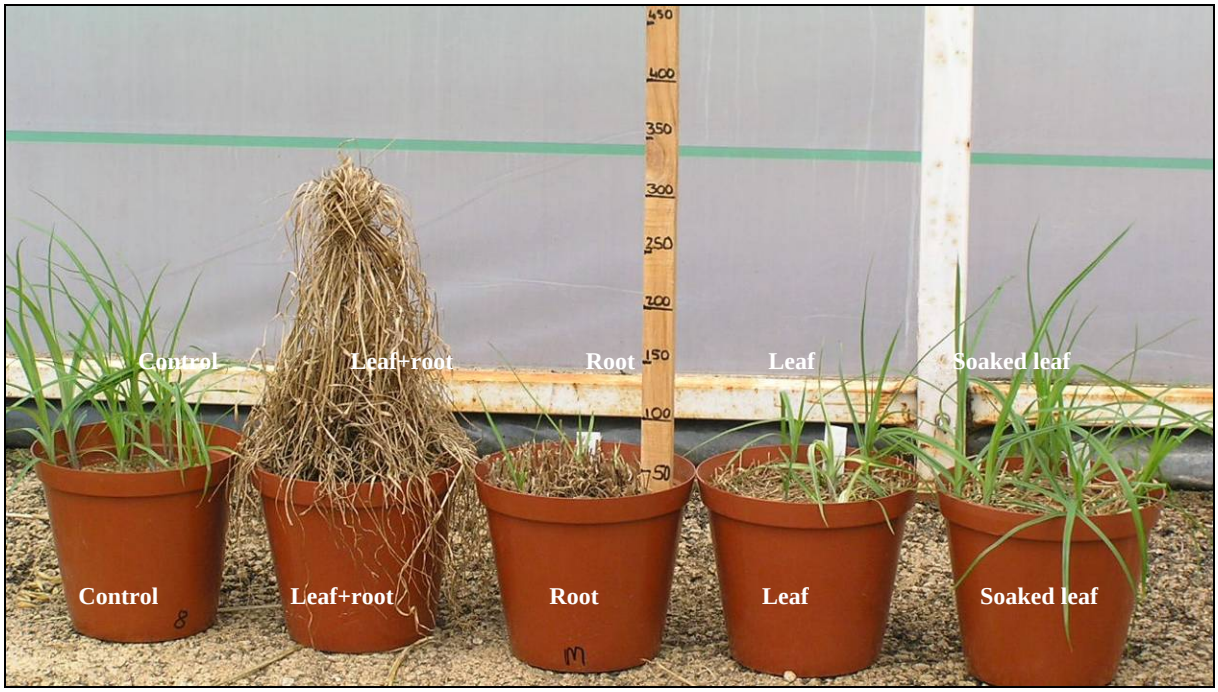

FIGURE 17 Influence of different annual ryegrass cv. 'Midmar' residue treatments on *C. esculentus* growth 21 days after emergence

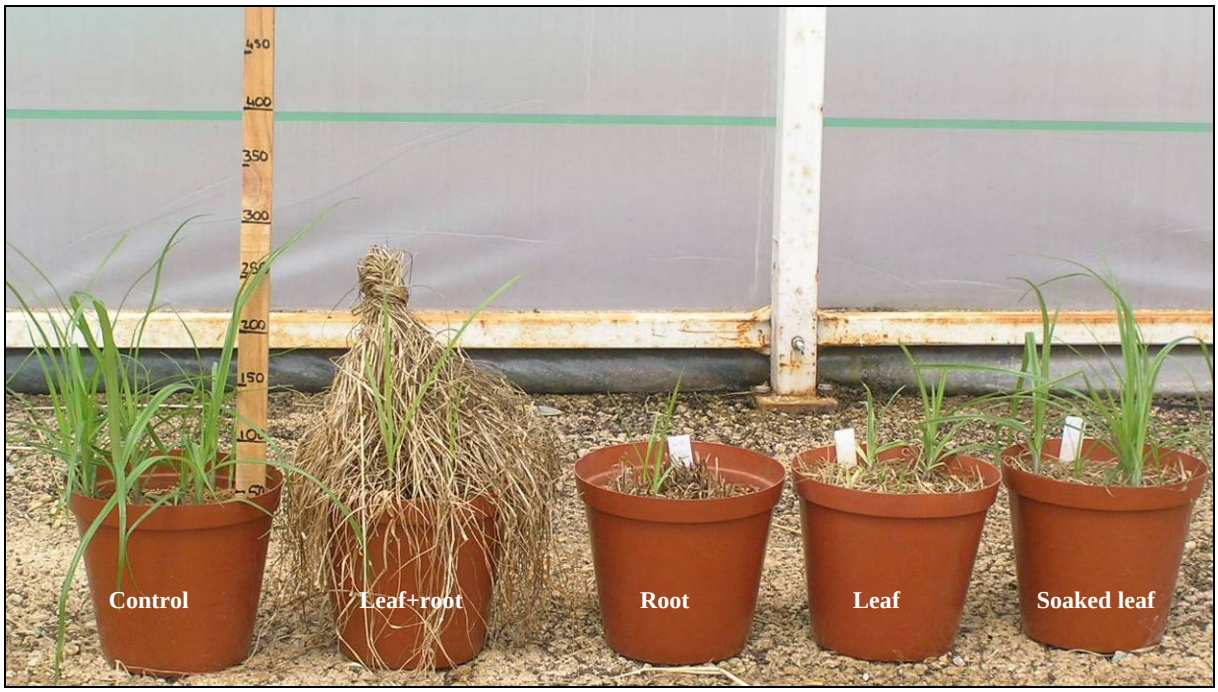

FIGURE 18 Influence of different annual ryegrass cv. 'Sophia' residue treatments on *C. esculentus* growth 21 days after emergence

3.5 Chemical analysis

Laboratory analysis indicated the presence of different concentrations of certain phenolic acids and benzoxazolin-2(3*H*)-one (BOA) in the leachate collected in the root treatment of the three annual ryegrass cultivars and oats (Table 12). The ryegrass cultivar 'Midmar' tested positive for three out of the four allelochemicals, followed by oats and the ryegrass 'Sophia' with two out of four. 'Midmar' had the highest concentrations of BOA and hydoxybenzoic acid compared to the other root treatments, and slightly less ferulic acid than oats. All three annual ryegrass cultivars exuded the allelochemical BOA through their roots with 'Midmar' and 'Sophia' containing hydroxybenzoic acid as well. The root leachate of oats contained ferulic acid and BOA. Vanillic acid was not detected in any of the root leachate of the cover crops tested.

TABLE 25 Concentrations of benzoxazolin-2(3*H*)-one (BOA) and three phenolic acids in the leachate collected from oats and annual ryegrass root material

	Phenolic acids			
	Vanillic acid	**Ferulic acid**	**Hydroxybenzoic acid**	**BOA**
	(ppb)			
Oats	0	16	0	7
Annual ryegrass				
cv. 'Agriton'	0	0	0	5
cv. 'Midmar'	0	14	440	20
cv. 'Sophia'	0	0	15	4

4. DISCUSSION

Stooling rye and annual ryegrass residues suppressed maize emergence and *C. esculentus* density in the field experiment. This is in agreement with Burgos and Talbert (1996), Reddy (2001) and Kravchenko and Thelen (2007) who found that residues of wheat (*Triticum aestivum*), stooling rye, oats and clovers (*Trifolium* spp.) suppressed sweet corn, soyabean (*Glycine max*) and maize emergence. The reduction was attributed to the creation of physical barrier, lower soil temperatures and allelopathy. However, results from the present study indicate that none of the above influenced maize emergence as no significant difference in emergence was observed amongst treatments, with and without residues. The conclusion that a physical barrier did not influence emergence in the field experiment, is therefore substantiated. There is a possibility that poor planting practices, such as insufficient seed coverage due to the amount of residue on the soil surface and planting by hand could have reduced maize emergence. Teasdale *et al.* (2008) reported reduced sweet corn emergence in stooling rye and vetch (*Vicia villosa*) residues but suggested that it was due to the planting procedure.

The differences observed in maize emergence in the field experiment were ascribed to possible fluctuations in soil temperature amongst the treatments. Teasdale and Mohler (1993) suggested that a delay in germination could be

expected with lower soil temperatures under cover crop residues. Temperatures measured in the present study varied amongst the treatments, however, it had no influence on maize emergence and therefore the conclusion drawn from the field experiment is refuted. Also, the lower temperature in the roots and control treatments is in contrast to findings of Kravchenko and Thelen (2007) who measured higher temperatures in wheat root and no-cover treatments compared to wheat straw and roots placed on top of the soil surface.

Ormeño-Núñez *et al.* (2008) found that a stooling rye mulch of 5 t ha^{-1} inhibited *C. esculentus* emergence and subsequent growth and suggested that it was due to allelopathy and the formation of a physical constraint. However, significantly fewer *C. esculentus* tubers sprouted in treatments containing root residues, implicating that the leaf residue layer did not, as expected, restrict emergence. The possibility that low soil temperatures and tuber size influenced emergence is small as *C. esculentus* tuber sprouting is more dependent on favourable moisture conditions than temperature and tuber size does not influence emergence (Stoller *et al.*, 1972).

Seedling growth can be influenced by variations in soil moisture and temperature, nutrient deficiencies and the presence of putative allelochemicals. Nutrient analysis of leachate and maize leaves collected from the different treatments indicated that nutrients were present in adequate quantities. This finding supports the conclusion that growth suppression measured in the field experiment was not due to N immobilization.

The influence of the leaf material treatment on growth was confounded to some extent by possible glyphosate damage (Figure 13). Maize and *C. esculentus* leaves were injured as the seedlings grew through the cover crop leaf residues containing glyphosate-isopropylamine residues. For confirmation purposes, ten Roundup- Ready and PHB 32D99 maize seeds were planted in plastic pots filled with sand and replicated five times. Unwashed cover crop leaf material was placed on the soil surface and pots were watered with a nutrient solution.

Roundup-Ready maize seedlings growing through the residues had no signs of leaf chlorosis, while especially the younger leaves of the non-Roundup-Ready cultivar, showed signs of leaf chlorosis. Tesfamariam *et al.* (2009) found in a pot experiment that the dry weight of sunflower seedlings (*Helianthus annuus*) was reduced after being planted into rye residues that were sprayed with glyphosate. They attributed the damage to the bio-availability of glyphosate in the stooling rye residues to subsequent cultivated crops.

FIGURE 19 Glyphosate damage symptoms on non-Roundup-Ready maize seedlings (bottom) compared to Roundup-Ready seedlings (top) growing through cover crop residues containing glyphosate-isopropylamine residues

Results from the field experiment indicated that growth inhibition was primarily due to the cover crop species as the annual ryegrass cultivar 'Midmar' inhibited maize and *C. esculentus* growth more than stooling rye, with both cover crops being more suppressive than the weed residues. This observation was confirmed in the pot experiment. Annual ryegrass suppressed maize and *C. esculentus*

growth the most followed by stooling rye and oats. Of the three annual ryegrass cultivars, 'Midmar' was the most suppressive. Reddy (2001) found that the total weed biomass was the lowest in ryegrass and the highest in stooling rye residues 10 weeks after soybean planting. Ryegrass also suppressed soyabean growth more than stooling rye. Similar results involving glucosinolate-producing cover crops and cultivars were reported by Norsworthy *et al.* (2007). *Digitaria sanguinalis* (crab finger-grass) growth was more reduced by Indian mustard [*Brassica juncea* (L.) Czer.] four weeks after bell-pepper (*Capsicum annuum*) transplanting than meadowfoam (*Limnanthes alba*), oilseed rape (*B. napus*) and brown mustard (*B. juncea* L.). They also highlighted the importance of cultivar selection as Indian mustard cultivar F-E75 resulted in greater *D. sanguinalis* control than Indian mustard cultivar F-L71.

In comparing the influence of separated cover crop root and leaf material, the root material of the different cover crop species caused more maize and *C. esculentus* growth inhibition than the leaf material. Differences in the extent of growth inhibitions by different plant parts have been reported previously with Barnes and Putnam (1986) indicating that rye shoots were the primary cause of growth inhibition but that root and shoot growth can act together in the field. Stone *et al.* (1998) pointed out that wheat growth was inhibited by both whole ryegrass plants and separated roots in comparison to interference from only leaves and stems and ryegrass interference with wheat primarily takes place below ground (Snaydon & Howe 1986). Breland (1996) concluded that the suppression of grain establishment after the incorporation of fresh annual ryegrass material was due to phytotoxic substances.

Growing the maize and *C. esculentus* in sand exposed the plants to higher concentrations of allelochemicals as soils with high organic matter and clay content generally retain allelochemicals more than sandy soil (Schmidt & Ley 1999). Allelochemicals are released from plant material through leaching, root exudation, decomposition and volatilization (Belz 2004). Chemical analysis of leachate collected from the roots treatment indicated the presence of known

allelochemicals. The root material contained higher concentrations of allelochemicals and upon decomposition of the material the allelochemicals were leached from the material. By soaking the leaf material overnight in water, allelochemicals were leached out of the material as indicated by the reduction in growth suppression by the soaked leaf material treatment compared to the others.

It is possible that the lower nutrient content in the roots treatment did not reduce growth *per se* but by inducing stressful conditions, the presence of the allelochemicals could have exacerbated the suppression of growth. Higher levels of BOA and 2,4-dihydroxy-2*H*-1,4-benzoxazin-3(4H) (DIBOA) were measured in stooling rye grown under low to moderate fertility than under high fertility (Mwaja *et al.*, 1995). The present chemical analysis also indicated that the annual ryegrass cultivar 'Midmar' contained higher concentrations of allelochemicals compared to the other two cultivars.

Allelochemical content not only differs amongst cultivars, but also over time. The concentration of DIBOA and BOA in eight field-grown cultivars of stooling rye ranged from 137–1469 μg g^{-1} dry tissue (Burgos *et al.*, 1999). Reberg-Horton *et al.* (2009) reported different DIBOA concentrations in stooling rye, depending on the cultivar and harvest date. Lower concentrations were measured later in the season except the late maturing cultivar 'Wheeler', which retained higher DIBOA concentrations later in the seasons than the other cultivars. BOA is released from DIBOA (2,4-dihydroxy-1,4 benzoxazin-3 one) during decomposition of residues or through root exudation (Chiapusio *et al.*, 2004). Because 'Midmar' tested positive for BOA, it had to contain DIBOA as well. The growth inhibition was therefore due to the combined effect both allelochemicals as it is unlikely that growth inhibition is due to BOA alone with DIBOA being more allelopathic than BOA (Burgos & Talbert 2000). However, the influence of the other two known allelochemicals as well as the unknown compounds present, should not be disregarded as the allelopathic effect on plants is often the result of a combination of these compounds (Einhellig 1996; Inderjit & Nayyar 2002).

5. CONCLUSIONS

The results of this study indicate clearly that the different cover crop species, cultivars and residue type affected maize and *C. esculentus* growth differently as both *C. esculentus* emergence and growth were inhibited but only maize seedling growth was suppressed. This effect will have to be taken in consideration when planning a weed control strategy involving cover crops. The presence of allelochemicals was confirmed in the different cover crop species, but the concentration thereof differed amongst cultivars and species. Presumably, the allelochemical content will also differ amongst the different residue types as the degree of suppression was different. Inhibition of maize and *C. esculentus* in the field experiment was therefore primarily caused by the presence of these allelochemicals and the extent of the inhibition was increased in the field experiment as both root decomposition and leaching from the leaf material occurred.

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APPENDIX B Statistical analysis

TABLE 1 ANOVA for the final emergence percentage of maize in the different cover crop residues

Source of variation	DF	SS	MS	VR	F pr
Block stratum	9	1325.2	147.3	2.07	
Block.*Units* Sratum					
Control	1	92.10	92.10	1.29	0.257
Control.Species	4	611.62	152.91	2.15	0.077
Control. Ryegrass vs oats+rye	1	191.61	191.61	2.69	0.103
Control. 'Sophia' vs 'Agriton'.'Midmar'	1	399.22	399.22	5.60	0.019
Control.Treat	3	1361.30	453.77	6.37	<0.001
Control. leaf+root vs root	1	887.01	887.01	12.45	<0.001
Control.leaf+soaked	1	48.41	48.41	0.68	0.411
Control.Species.Treat	12	1127.82	93.98	1.32	0.211
Control. Ryegrass vs Oats+rye. leaf+root vs root	1	96.93	96.93	1.36	0.245
Control. 'Sophia' vs 'Agriton'.'Midmar'. leaf+root vs root	1	0.69	0.69	0.01	0.922
Control. Ryegrass vs Oats+rye. leaf+soaked	1	156.47	156.47	2.20	0.140
Control. 'Sophia' vs 'Agriton'.'Midmar'. leaf+soaked	1	84.11	84.11	1.18	0.279
Residual	175	12470.5			
TOTAL	**204**	**16924.9**			

TABLE 2 ANOVA for the final emergence percentage of *C. esculentus* in the different cover crop residues

Source of variation	DF	SS	MS	VR	F pr
Block stratum	9	4429.0	492.1	1.98	
Block.*Units* Sratum					
Control	1	4140.2	4140.2	16.69	<0.001
Control.Species	4	208.0	52..0	0.21	0.933
Control. Ryegrass vs oats+rye	1	200.1	200.1	0.81	0.370
Control. 'Sophia' vs 'Agriton'.'Midmar'	1	6.7	6.7	0.03	0.870
Control.Treat	3	44269.5	14756.5	59.50	<0.001
Control. leaf+root vs root	1	3025.0	3025.0	12.20	<0.001
Control.leaf+soaked	1	1764.0	1764.0	7.11	0.008
Control.Species.Treat	12	1208.0	100.7	0.41	0.960
Control. Ryegrass vs Oats+rye. leaf+root vs root	1	150.0	150.	0.60	0.438
Control. 'Sophia' vs 'Agriton'.'Midmar'. leaf+root vs root	1	367.5	367.5	1.48	0.225
Control. Ryegrass vs Oats+rye. leaf+soaked	1	20.2	20.2	0.08	0.776
Control. 'Sophia' vs 'Agriton'.'Midmar'. leaf+soaked	1	140.8	140.8	0.57	0.452
Residual	180	44641.0			
TOTAL	**209**	**98895.7**			

TABLE 3 ANOVA for the height growth of maize in the different cover crop residues

Source of variation	DF	SS	MS	VR	F pr
Block stratum	9	2190.2	243.4	1.56	
Block.*Units* Sratum					
Control	1	18117.6	18117.6	116.48	<0.001
Control.Species	4	4189.6	1047.4	6.73	<0.001
Control. Ryegrass vs oats+rye	1	1529.8	1529.8	9.83	0.002
Control. 'Sophia' vs 'Agriton'.'Midmar'	1	1953.4	1953.4	12.56	<0.001
Control.Treat	3	107383.8	35794	230.12	<0.001
Control. leaf+root vs root	1	1252.4	1252.4	8.05	0.005
Control.leaf+soaked	1	42883.1	42883.1	275.70	<0.001
Control.Species.Treat	12	6491.4	541.0	3.48	<0.001
Control. Ryegrass vs Oats+rye. leaf+root vs root	1	1143.0	1143.0	7.35	0.007
Control. 'Sophia' vs 'Agriton'.'Midmar'. leaf+root vs root	1	907.7	907.7	5.84	0.017
Control. Ryegrass vs Oats+rye. leaf+soaked	1	1939.7	1939.7	12.47	<0.001
Control. 'Sophia' vs 'Agriton'.'Midmar'. leaf+soaked	1	232.5	232.5	1.49	0.223
Residual	175	27220.3	155.5		
TOTAL	**204**	**162222.5**			

TABLE 4 ANOVA for the diameter growth of maize seedlings in the different cover crop residues

Source of variation	DF	SS	MS	VR	F pr
Block stratum	9	0.112	0.012	1.67	
Block.*Units* Sratum					
Control	1	0.418	0.418	56.17	<0.001
Control.Species	4	0.176	0.044	5.93	<0.001
Control. Ryegrass vs oats+rye	1	0.031	0.031	4.18	0.043
Control. 'Sophia' vs 'Agriton'.'Midmar'	1	0.058	0.058	7.82	0.006
Control.Treat	3	7.362	2.454	329.75	<0.001
Control. leaf+root vs root	1	0.016	0.016	2.12	0.147
Control.leaf+soaked	1	0.189	0.189	25.39	<0.001
Control.Species.Treat	12	0.613	0.051	6.87	<0.001
Control. Ryegrass vs Oats+rye. leaf+root vs root	1	0.00007	0.00007	0.01	0.924
Control. 'Sophia' vs 'Agriton'.'Midmar'. leaf+root vs root	1	0.010	0.010	1.32	0.252
Control. Ryegrass vs Oats+rye. leaf+soaked	1	0.104	0.104	13.92	<0.001
Control. 'Sophia' vs 'Agriton'.'Midmar'. leaf+soaked	1	0.010	0.010	1.33	0.251
Residual	175	1.302	0.007		
TOTAL	**204**	**9.651**			

TABLE 5 ANOVA for the number of fully expanded leaves of maize seedlings in the different cover crop residues

Source of variation	DF	SS	MS	VR	F pr
Block stratum	9	0.87	0.10	0.92	
Block.*Units* Sratum					
Control	1	3.01	3.01	28.66	<0.001
Control.Species	4	5.17	1.29	12.30	<0.001
Control. Ryegrass vs oats+rye	1	0.83	0.83	7.86	0.006
Control. 'Sophia' vs 'Agriton'.'Midmar'	1	1.96	1.96	18.68	<0.001
Control.Treat	3	43.04	14.35	136.56	<0.001
Control. leaf+root vs root	1	20.00	20.00	190.37	<0.001
Control.leaf+soaked	1	14.00	14.00	133.22	<0.001
Control.Species.Treat	12	6.27	0.52	4.97	<0.001
Control. Ryegrass vs Oats+rye. leaf+root vs root	1	1.66	1.66	15.84	<0.001
Control. 'Sophia' vs 'Agriton'.'Midmar'. leaf+root vs root	1	0.72	0.72	6.87	0.010
Control. Ryegrass vs Oats+rye. leaf+soaked	1	1.73	1.73	16.42	<0.001
Control. 'Sophia' vs 'Agriton'.'Midmar'. leaf+soaked	1	0.63	0.63	6.02	0.015
Residual	175	18.38	0.11		
TOTAL	**204**	**75.16**			

TABLE 6 ANOVA for the dry weight per plant of maize seedlings in the different cover crop residues

Source of variation	DF	SS	MS	VR	F pr
Block stratum	9	0.13	0.01	0.86	
Block.*Units* Sratum					
Control	1	0.52	0.52	31.38	<0.001
Control.Species	4	0.85	0.21	12.82	<0.001
Control. Ryegrass vs oats+rye	1	0.21	0.21	12.41	<0.001
Control. 'Sophia' vs 'Agriton'.'Midmar'	1	0.50	0.50	29.71	<0.001
Control.Treat	3	17.41	5.80	348.11	<0.001
Control. leaf+root vs root	1	0.01	0.01	0.80	0.373
Control.leaf+soaked	1	3.38	3.38	202.86	<0.001
Control.Species.Treat	12	1.07	0.90	5.38	<0.001
Control. Ryegrass vs Oats+rye. leaf+root vs root	1	0.002	0.002	0.16	0.687
Control. 'Sophia' vs 'Agriton'.'Midmar'. leaf+root vs root	1	0.006	0.006	0.39	0.534
Control. Ryegrass vs Oats+rye. leaf+soaked	1	0.23	0.23	13.58	<0.001
Control. 'Sophia' vs 'Agriton'.'Midmar'. leaf+soaked	1	0.03	0.03	2.06	0.453
Residual	175	2.90	0.02		
TOTAL	**204**	**22.26**			

TABLE 7 ANOVA for the dry weight per plant of *C. esculentus* seedlings in the different cover crop residues

Source of variation	DF	SS	MS	VR	F pr
Block stratum	9	0.06	0.007	1.62	
Block.*Units* Sratum					
Control	1	0.14	0.14	33.59	<0.001
Control.Species	4	0.08	0.02	4.66	0.001
Control. Ryegrass vs oats+rye	1	0.04	0.04	9.80	0.002
Control. 'Sophia' vs 'Agriton'.'Midmar'	1	0.02	0.02	5.17	0.024
Control.Treat	3	1.98	0.66	161.75	<0.001
Control. leaf+root vs root	1	0.001	0.001	0.45	0.503
Control.leaf+soaked	1	0.66	0.66	160.80	<0.001
Control.Species.Treat	12	0.14	0.01	2.87	0.001
Control. Ryegrass vs Oats+rye. leaf+root vs root	1	0.0002	0.0002	0.07	0.796
Control. 'Sophia' vs 'Agriton'.'Midmar'. leaf+root vs root	1	0.0004	0.0004	0.11	0.744
Control. Ryegrass vs Oats+rye. leaf+soaked	1	0.01	0.01	2.73	0.100
Control. 'Sophia' vs 'Agriton'.'Midmar'. leaf+soaked	1	0.06	0.06	14.19	<0.001
Residual	173	0.71			
TOTAL	**202**	**3.03**			

SUMMARY

Currently, global food prices are on the increase and it is reaching values higher than in 2008, forcing those who spend half of their income on food into poverty (Parker, 2011). In future, food production will have to increase to meet the higher demand because of the rise in the global population. This will be more difficult than during the Green Revolution in the 1960s due to the reduced availability of land and water resources and policies regarding fertilizer and pesticide use. With the pressure of sustainable food production in environmentally benign ways, and the recent surge in crop production input costs on a global scale, crop producers are compelled to change or adapt current production systems. In South Africa, previous unsustainable crop production practices have contributed to a decline in soil stability, leading to topsoil losses, and therefore fertile production areas. Land users are obliged by law to adhere to the Conservation of Agricultural Resources Act of 1983 to conserve natural resources, by among other things, combating and preventing soil erosion and maintaining the production potential of the soil. For achieving these goals, methods such as conservation tillage, suitable conservation works, avoidance of cultivation during periods of high erosion hazard and the inclusion of cover crops in their cultural practices, are advised.

Weed interference is a given in any crop production situation, leading to potentially high yield losses if weeds are not adequately controlled. With the introduction of herbicides, producers were able to simplify their weed management with the added advantages of it being reliable, effective and relatively inexpensive. This created the impression that weed control was fairly undemanding. The focus therefore shifted from a long-term weed management strategy aiming to reduce weed density through cropping systems, to the reliance on chemical weed control directed at controlling weed seedlings just prior to, or shortly after crop establishment. Reliance on chemical control only, has drawbacks, such as the development of herbicide resistance, the potential negative impact on food and environmental safety and the failure to control

weeds due to adverse climatic conditions or application errors. Therefore, weed management should focus not only on curative methods but instead on combining different cultural methods to prevent and manage weed populations. Cultural weed management includes any adjustments or modifications to production practices that would improve crop competitiveness and reduce weed density such as manipulating plant populations and planting dates, using crop cultivars adapted to the climatic conditions, including different crop rotations and using cover crops in combination with conservation tillage, to mention a few. Cover crops not only improve soil conditions, but can suppress weed establishment and growth thereby reducing weed populations to a level below the threshold value where weeds start to interfere with crop growth. This is achieved through changes in the growth environment such as excluding light reaching the soil surface, creating a physical barrier and through the release of allelochemicals from the cover crop residues. The question that needs to be asked is whether cultural practices will be able to provide a substantial contribution to weed management.

Research has been done on various aspects of conservation tillage in KwaZulu-Natal (KZN), but research on the use of cover crops in a crop production system for weed control is lacking. Information and an understanding of the ability of cover crops to suppress weed growth and the subsequent effect on crop growth in a conservation tillage system are vital if principles were to be developed on the use of cover crops for weed management in KZN. Based on the knowledge generated, farmers can be assisted in the implementation of supplemental weed control methods as weed management is a difficult aspect of conservation tillage. If proven effective, the use of cover crops, alone or in combination with herbicides, can in the long term prove not only to be more economical as less herbicides could be used, thereby lowering the chemical input costs, but also contribute to a more environmentally balanced crop production system. In KZN, maize (*Zea mays*) is the most important grain crop and contributes to 4.6% of the total maize production in South Africa. As is the case in the rest of the world, *Cyperus esculentus* (yellow nutsedge) is one of the most difficult weeds to control

and in a conservation tillage system it, among others, can become a dominant and difficult weed to manage if weed control is ineffective (Fowler, 2000). A research project was implemented in KZN to test the hypothesis that cover crops would suppress *C. esculentus* growth without compromising the growth of maize.

In a field experiment done over four consecutive years with two cover crops, stooling rye (*Secale cereale*) cultivar 'Agri-Blue' and annual ryegrass (*Lolium multiflorum*) cultivar 'Midmar', maize emergence was suppressed by the residues of both cover crop species compared to treatments without any residues. For 14 days after emergence (DAE), early maize growth was similar between all treatments, regardless of the presence of cover crop and weed residues on the soil surface. Thereafter, maize growth was suppressed by the residues compared to non-residue treatments. Despite both cover crops having similar amounts of biomass on the soil surface, annual ryegrass suppressed maize growth more than stooling rye residues. *C. esculentus* growth was severely inhibited in the inter-row maize planting lines by annual ryegrass residues for 14 DAE, whereafter the growth suppression progressively diminished. Although stooling rye suppressed *C. esculentus* growth to a lesser extent than that of annual ryegrass, the suppression lasted longer. Results also indicated that growth seasons had a significant impact on the ability of the cover crops to suppress crop and weed growth, with more suppression occurring during warm, wet conditions rather than under warm/dry and cold/wet conditions.

Physical obstruction by the residues did not influence maize emergence but the possibility of lower soil temperatures underneath the cover crop mulch could have suppressed emergence leading to lower maize plant populations. The main cause of maize and *C. esculentus* growth suppression is however attributed to the release of allelochemicals from the cover crop residues. Although no maize growth differences were seen between the different treatments for 14 DAE, it is likely that during this time, the maize seedlings absorbed allelochemicals released by the cover crop residues, thereby reducing their fitness. Also, the cover crop residues suppressed *C. esculentus* growth, thereby reducing competition

with maize for resources. However, after 14 DAE, *C. esculentus* growth increased to such an extent that the threshold value was reached where competition for growth resources started to impact negatively on maize seedling growth. Despite fierce *C. esculentus* competition in the weeds treatment due to higher *C. esculentus* densities, maize growth reduction in this treatment was less compared to the cover crop treatments as maize growth was not compromised by the presence of allelochemicals leached from the cover crop residues. Maize seedlings in the cover crop residues could not recover from the influence of allelopathy and *C. esculentus* competition, which culminated in significantly lower maize yields. It is further possible that the difference in the allelopathic potential of the two cover crops was responsible for the difference in their effect on maize seedling growth.

In order to seek confirmation of the allelopathy-based hypothesis, an investigation on the influence of different cover crop species and residue types on maize and *C. esculentus* emergence and growth under controlled conditions, was initiated. Cover crops selected included those used in the field trial namely stooling rye, cultivar 'Agri-Blue' and annual ryegrass cultivar 'Midmar', together with oats (*Avena sativa*) cultivar 'Heros' and two additional annual ryegrass cultivars 'Agriton' and 'Sophia'. Oats was included as it is known for its weed control abilities (Campiglia *et al*., 2010), while different annual ryegrass cultivars were evaluated due to possible cultivar differences in their allelopathic potential. The cover crops were sown in pots according to field-recommended seeding rates and grown for 21 weeks, whereafter plants were killed by spraying them with glyphosate-isopropylamine. Two weeks after killing the cover crops, maize seeds and *C. esculentus* tubers were planted into pots containing different types of cover crop residues. These residues included both cover crop leaf and roots left intact in the pots, and only root residues left undisturbed in the pots. The leaf material collected from the pots containing only root residues were then placed on previously unused sand to eliminate the possible influence of the root material. An equal portion of the same leaf material was soaked overnight in water before being placed on unused sand.

Confirmation was obtained that differences in maize emergence in the field experiment was not due to a physical obstruction. Maize emergence was not influenced by the different residue types while *C. esculentus* emergence was severely inhibited by treatments containing root residues. Overall, annual ryegrass residues suppressed maize and *C. esculentus* seedling growth the most while oats and stooling rye had similar but lesser effects. Cultivar differences were observed with the cultivar 'Midmar' being the most suppressive followed by 'Agriton' and 'Sophia'. With regards to residue type, the root residues inhibited growth the most followed by the leaf+root residues. Growth was the least affected by the two leaf material treatments although the influence of the unsoaked leaf material treatment was confounded by unexpected glyphosate-isopropylamine damage as a result of the herbicide being absorbed by maize and *C. esculentus* developing through the cover crop residues killed by the herbicide. It was further evident that by soaking the leaf material overnight in tap water, the suppressive qualities of the leaf material were reduced, which pointed to allelochemicals having been present in the leaf material prior to soaking. The soaking could also have removed glyphosate residues from the leaves, improving maize growth.

Chemical analysis of the leachate collected from the root material of the three annual ryegrass cultivars and oats indicated the presence of two known phenolic allelochemicals, ferulic and p-hydroxybenzoic acid as well as the benzoic acid benzoxazolin-2(3*H*)-one (BOA). Because BOA is released from 2,4-dihydroxy-1,4 benzoxazin-3 one (DIBOA) during decomposition of residues, or through root exudation (Chiapusio *et al.*, 2004), the cover crop species tested would probably contain DIBOA as well. Difference in allelochemical content was established amongst the cover crop species and cultivars with 'Midmar' having the highest concentrations of BOA and p-hydroxybenzoic. Results of the pot trial confirmed for the first time the presence of three known allelochemicals in annual ryegrass as well as concentration differences amongst annual ryegrass cultivars. This could explain the higher growth inhibition of maize and *C. esculentus* when exposed to 'Midmar' residues compared to the other cover crop species.

The allelopathy-based hypothesis was therefore confirmed. The findings suggest that the growth of difficult-to-control weeds could be suppressed by allelopathic cover crops in a maize conservation tillage system in KZN but that crop growth was at risk. It is therefore possible that with the use of cover crops, the growth of other weed species could be suppressed as well. Principles regarding the use and management of cover crops would have to balance the weed growth suppression gained by the residues with minimizing the reduction in crop growth.

To reduce the negative influence of cover crop residues on crop growth, various options could be considered. The degree of crop growth reduction is dependent on the cover crop species and cultivar. By evaluating different cover crop species and cultivars, a combination could be selected that would optimize weed growth and minimize crop injury. Killing the cover crop at planting of the main crop could reduce the risk to crop growth as seedlings would be exposed to initially slow allelochemical release from relatively fresh residues, resulting in lower allelochemical concentrations in the root zone during the vulnerable seedling stage. Subsequent crop seedling growth could further be enhanced by planting cultivars with a vigorous growth habit, adapted to local soil and climatic conditions. Exposing the crop to minimal cover crop residues in the planting line could also lessen the impact on crop growth. If the residues were removed from the planting lines, for example by practising strip-tillage, the allelochemical content in the root zone would be lower, thereby reducing the negative influence on crop growth.

Weed suppression is mainly determined by the cover crop species and cultivar. It not only influences the period of residue decomposition and subsequent availability of allelochemicals, but also the potential concentration of allelochemicals which is a function of the biomass production capabilities of the cover crop species and cultivar. Ideally, allelochemicals must be released from the residues over an extended period to prolong weed growth reduction. The soil and climatic conditions would also determine allelochemical release from the decaying residues and the allelochemical concentration in the root zone, thereby

impacting on the degree of weed growth suppression. Manipulation of the cover crop killing date could extend the period of weed suppression due to the prolonged presence of the residues on the soil surface, but the subsequent negative influence on crop growth could also be increased. Although cover crops can provide a substantial contribution to weed management, in order to achieve prolonged, effective weed control, the combination of cover crop residues on the soil surface and the application of herbicides will probably be required. It could for example result in pre-emergence herbicide application to the planting rows only instead of broadcast applications or chemical control could be restricted to post-emergence herbicide use. Using glyphosate tolerant cultivars could also be beneficial, with weed control being less complicated. The extent to which herbicides will be used is dependent on the degree of weed suppression achieved by the cover crop residues.

Certain constraints and barriers, however, limit the adoption and implementation of cover crops in a weed management system. No ready-to-use technology for allelopathy mediated weed prevention and control can be given to farmers. Recommendations will have to be based on their management level, cultural practices used, climatic and soil conditions, economic considerations and social requirements. The practice is not ideal for the rural areas of KZN due to the communal land tenure system which limits the right of the farmer to the use of the land to the season the crop is grown. After the crop is harvested, the fields are used for grazing, making the use of cover crops impossible. The involvement of various crop production systems also increases the complexity of the weed management system for both small-scale and commercial farmers.

In conclusion, the use of cover crops for weed control should be considered a tool that is supplementary/complementary to standard weed control practices aiming at managing weed populations in the long-term. The principles are not restricted to KZN, but can be applied to the rest of South Africa. Future research should include the evaluation of the weed suppression abilities of different cover crop species and cultivars, the influence on crop and weed growth through

manipulation of the cover crop killing date and the evaluation of different herbicide application times and rates. A question that needs to be answered is whether the main crop could recover adequately, producing acceptable yields, after being exposed to the cover crop residue in the root zone if weed competition is limited.

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