Physical and allelopathic effects of crop residue on wheat, barley and canola production

by

Theunis Nicolaas Kotzé

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Supervisor: Dr. PA Swanepoel

Co-supervisor: Dr. PJ Pieterse

Co-supervisor: Dr. JA Strauss

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Declaration

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Theunis Nicolaas Kotzé

Date: March 2021

Summary

Retention of crop residue has many benefits such as moisture conservation, improvement of soil health and reduction in soil erosion. Residue retention together with no-tillage and crop diversification (crop rotation) are classified as Conservation Agriculture (CA). However, the adoption of CA comes with challenges of planting into large crop residue loads, especially when livestock is not part of the system. Certain crop residue types and loads may lead to yield penalties for the subsequent crop. Past studies have indicated that allelopathy, physical effects or chemical soil processes might be the cause. This study aimed to investigate the influence of crop residue on the subsequent wheat (*Triticum aestivum*), barley (*Hordeum vulgare*) and canola (*Brassica napus*) as well as identify the possible mechanisms responsible for driving productivity. Laboratory and glasshouse trials were conducted to evaluate effects of crop residue that had time to degrade prior to planting the next season's crop, on the early growth of wheat, barley and canola. Extracts were made from various residues and the allelopathic effects of the extracts were evaluated on the germination, coleoptile and radicle lengths of seedlings. Germination was affected ($p < 0.05$) in barley and canola, but not in wheat ($p > 0.05$). The coleoptile and radicle lengths were affected more adversely ($p < 0.05$) than germination percentages. Some residue types led to decreases in the coleoptile and radicle lengths, while other residue types promoted them slightly. Crop residue still had an allelopathic potential even after degradation for one year in the field. However, in the presence of soil in the glasshouse, the allelopathic effects became negligible ($p > 0.05$). The canola with its small seed size was influenced ($p < 0.05$) by a large residue load of 8000 kg ha^{-1}, which reduced early growth. A field trial evaluated performance of a single and a double disc planter and management of the residue loads, as well as the effect of various residue types on production of wheat, barley and canola. The double disc planter led to better wheat and barley establishment while the single disc planter led to better canola establishment ($p < 0.05$). The double disc planter cleaned the seed furrow more, while the single disc planter had better depth control. Allelopathy was negligible and physical effects was limited in this study due to relatively small residue loads, mostly under 5000 kg ha^{-1}. The effect of crop residue on soil processes likely had the biggest influence on the subsequent crop. Crop residue types which resulted in the highest N mineralisation rate led to better yields in year two ($p < 0.05$), while in year one residue types which produced larger residue loads have led to slightly better yields due to moisture conservation. In a residue decomposition trial, effects of soil faunal communities and residue types on decomposition were tested. Soil fauna fragmented residue leading to faster decomposition. Residue types with lower C:N ratios decomposed faster. Retaining appropriate amounts of residue for a particular crop will minimise negative effects while retaining the benefits.

Opsomming

Die bedekking van grond met gewas residu het verskeie voordele naamlik vog bewaring, beter grond gesondheid asook die afname in grond erosie. Die behoud van gewas residu te same met minimum bewerking en gewas diversifikasie (gewas rotasie) word geklassifiseer as Bewarings Boerdery. Die implimentering van Bewarings Boerdery praktyke kom egter nie sonder uitdagings nie soos om te plant in dik gewas residu ladings. Die bogenoemde is veral ‘n uitdaging is stelsels waar vee nie geïntegreer word nie. Sekere tipes gewas residu en ladings mag laer opbrengste tot gevolg hê. Vorige studies dui aan dat allelopatiese, fisiese effekte asook chemiese grond prosesse verantwoordelik is. Die mikpunt van hierdie studie was om die invloed van gewas residu op die opeenvolgende koring (*Triticum aestivum*), gars (*Hordeum vulgare*) en kanola (*Brassica napus*) gewas te evalueer asook die identifisering van moontlike verantwoordelike meganismes wat die produktiwiteit dryf. Laboratorium en glashuis proewe was gedoen met residu wat tyd gehad het om te verweer, op die vroeë groei van koring, gars en kanola. Ekstrakte was gemaak van verskeie tipes residu en was geevalueer op die ontkieming, koleoptiel en radikaal lengtes van saailinge. Die ontkieming van gars en kanola was geaffekteer ($p < 0.05$), maar nie koring nie ($p > 0.05$). Die koleoptiel en radikaal lengtes was baie meer geaffekteer ($p < 0.05$) in vergelyking met die ontkieming. Sekere gewas residu tipes het die koleoptiel en radikaal lengtes verminder terwyl ander effense verlenging tot gevolg gehad het. Die gewas residu was steeds allelopaties selfs na vewering in die veld. Alleloptiese effekte het egter weglaatbaar ($p > 0.05$) geword as grond ingesluit word. Kanola wat ‘n klein saad grote het was egter beïnvloed ($p < 0.05$) deur groot residu ladings van 8000 kg ha^{-1} wat swak vroeë groei tot gevolg gehad het. Die veldproef het ‘n enkelskyf en ‘n dubbelskyf planter evalueer in hulle vermoë om residu ladings te hanteer asook die effek van verskeie gewas residu tipes op koring, gars en kanola produksie. Die dubbelskyf planter het tot beter koring en gars vestiging gelei terwyl die enkelskyf planter kanola beter gevestig het ($p <$ 0.05). Die dubbelskyf planter het die saadvoor beter skoon gemaak terwyl die enkelskyf planter beter diepte beheer gehad het. Allelopatie was weglaatbaar en fisiese effekte was klein as gevolg van relatiewe klein residue ladings wat meestal onder 5000 kg ha^{-1} was. Die effek wat gewas residu op die grond prosesse gehad het, het moontlik die grootse invloed gehad op die opeenvolgende gewas. Gewas residu tipes wat tot meer minerale stikstof in die grond gelei het, het beter opbrengste tot gevolg gehad in jaar twee ($p <$

0.05). In jaar een was beter opbrengste egter verkry in residu tipes was groter residu ladings tot gevolg gehad het, dit kan toegeskryf word aan beter vog bewaring. ‘n Residu afbraak proef het die effek van grond fauna gemeenskappe en residu tipes evalueer. Grond fauna het die residu gefragmenteer wat vinniger afbraak tot gevolg gehad het. Residu tipes met laer C:N verhoudings het vinniger af gebreek. Die behoud van ‘n geskikte hoeveelheid gewas residu vir ‘n spesifieke opeenvolgende gewas sal negatiewe effekte beperk terwyl die voordele behou word.

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Preface

This thesis is presented as a compilation of six chapters.

Chapter 1	**General introduction**
Chapter 2	**The effects of crop residue on barley, canola and wheat yield: A meta-analysis of field trials**
Chapter 3	**Allelopathic effects of crop residues on germination and early growth of wheat, barley and canola**
Chapter 4	**Evaluating crop residue effects and disc planter residue handling on wheat, barley and canola production**
Chapter 5	**Decomposition of different types of crop residue in response to soil faunal decomposer communities**
Chapter 6	**General conclusion and future research**

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List of abbreviations

C	Carbon
CA	Conservation Agriculture
CT	Conventional tillage
cv.	Cultivar
DAE	Days after emergence
N	Nitrogen
NT	No-tillage
PM	Physiological maturity
RT	Reduced tillage
s.a.	Sino anno
SE	Standard error
ST	Shallow tillage

Chapter 1: General Introduction

The Southern Cape of South Africa has a Mediterranean type climate and receives most of its rain during the winter months. The rainfall may however be very sporadic in drought years resulting in crop failure. Adopting Conservation Agriculture (CA) practises can enhance the soil organic carbon pool, and in turn improve the agronomic productivity (Lal 2006). The three key principles of Conservation Agriculture (CA) is residue retention together with no-tillage and crop diversification (Swanepoel *et al.* 2019). Residue retention promotes the conservation of soil moisture, nutrient cycling, soil health and limits erosion, among other benefits (Turmel *et al.* 2015). Conservation Agriculture can therefore improve environmental, agronomic and economic sustainability in relatively dry Mediterranean climates (Calzarano *et al.* 2018).

The retention of large residue loads may however lead to yield penalties (Bruce *et al.* 2005; Wynne *et al.* 2019). The negative effects when retaining a large residue load may be attributed to allelopathy, physical effects, or soil processes. Allelopathy can be defined as the (bio-)chemical interaction amongst plants including those mediated by microorganisms (Weston and Duke 2003). Physical effect can be described as the overshadowing as well as weight of the residue on the crop. Crop residue may alter soil processes such as nitrogen immobilisation when incorporated (Kimber 1973). Understanding the mechanisms at work will enable producers to adapt management strategies to minimise or mitigate them while retaining the benefits of residue retention.

The potential negative effects experienced when a large residue load is retained may in some cases be attributed to allelopathy (Lovett and Jessop 1982). Crops such as wheat (*Triticum aestivum*) and barley (*Hordeum* vulgare) are known for hydroxamic acids which influence cell membranes while the *Brassica spp.* are known to contain thiocyanates (Weston and Duke 2003). The potential of residue to be allelopathic are well known and has been proven in laboratory trials (Wynne *et al.* 2019). Different crops and even different varieties of the same crop reacts differently to allelochemicals (Wu *et al.* 2001). The question however arises if residue has an allelopathic effect on the next crop, in particular if there is an extended time period before the next crop is sown. The allelochemicals may be leached, adsorbed or transformed by microbes and lose their toxicity to the crop plants (Wu *et al.* 2001). When the residue has time to degrade it becomes less toxic compared to fresh residue (Purvis 1990). The crops in the southern Cape are harvested in November and the next crop is seeded in May the following year, thus one would expect the crop residue to be degraded and less toxic.

Potential physical effects of residue include overshadowing, physical weight of the residue and cold temperature under the residue layer leading to poor early growth (Bruce *et al.* 2006). Seedlings have to expend energy reserves to penetrate large residue loads and in turn less reserves remain to be invested in the early leaf development (Bruce *et al.* 2006). The overshading of the seedlings by a large residue load may lead to reduced photosynthetically active radiation (Bruce *et al.* 2006). The retention of residue may result in low soil temperature (Roberts *et al.* 2005). The low soil temperature may lead to slower early growth among plants (Unger 1978) and reduce the metabolic rate of seedling development (Porter and Gawith 1999). Seeding into big residue loads presents its own challenges. Tine planters tend to get clogged in large residue loads while disc planters may push residue into the seed slot (hair pinning) under moist conditions (Morris *et al.* 2010). Residue management has to be done while harvesting the previous year, short chopped residue tends to flow better around tines (Morris *et al.* 2010). Proper seed to soil contact can be an issue when a lot of residue is retained on the soil surface leading to reduced uptake of water (Kong 2014).

The retention of residue has several impacts on soil processes such as possible nitrogen immobilisation and nutrient cycling. When residue with a high C:N ratio is incorporated the possibility arises for nitrogen to be immobilised (Kimber 1973). When residue is left on the soil surface the possibility for nitrogen immobilisation becomes negligible (Ferreira and Reinhardt 2010). Residue retention however leads to increased nutrient cycling (Turmel *et al.* 2015). The retention of residue together with no-tillage led to higher microbial biomass compared to systems where residue was removed and the soil was tilled conventionally (Saikia *et al.* 2019). Residue decomposition is mediated by soil biota thus by managing systems in such a manner that is favourable to the increase of soil biota, it may lead to quicker residue decomposition and ultimately nutrient cycling (Carlesso *et al.* 2019). The degradation of soils is associated with imbalanced, inadequate and pro-macronutrient fertilizer use together with the inadequate use of crop residue (Gupta *et al.* 2018). Thus, by retaining residues, we may ultimately reduce our dependence on macronutrient fertilisers, which may improve soil health.

This study aims to investigate the influence of crop residue on the subsequent wheat, barley and canola crop and identify the possible mechanisms responsible. The first objective is to evaluate the effect of crop residue extracts on the germination and germination parameters. The second objective aims to distinguish between physical and allelopathic effects of wheat residue on early growth of wheat, barley and canola under controlled conditions. The first two objectives were addressed in chapter 3. The third objective of this study is to evaluate the effect of different types of crop residue and two types of disc planters on crop production in the Southern Cape of South Africa (Chapter 4). The fourth objective is to determine the rate of decomposition of different crop residue types and the influence that micro-, meso- and macro fauna communities has on crop decomposition (Chapter 5).

1.2 Layout of thesis

The thesis consists of six chapters. Chapter one provides a background on crop residue retention and identifies gaps in research. The aim and objectives of the study is provided in this chapter.

Chapter 2 comprises of a literature review in the form of a meta-analysis. The meta-analysis investigated the effect of crop residue load on the wheat, barley and canola yield. This chapter was submitted to the South African Journal of Plant and Soil. The article can be cited as follow: Kotzé TN, Pieterse PJ, Strauss JA, Swanepoel PA. (s.a.). The effects of crop residue on barley, canola and wheat yield: A meta-analysis of field trials. South Africa Journal of Plant and Soil (under review).

Chapter 3 comprises of a laboratory trial and a glasshouse trial that evaluated the allelopathic potential of crop residue in the absence and in the presence of soil. This chapter was submitted to Crop Science. The article can be cited as follow: Kotzé TN, Pieterse PJ, Strauss JA, Swanepoel PA. (s.a.). Allelopathic Effects of Crop Residues on Germination and Early Growth of Wheat, Barley and Canola. Crop Science (under review).

Chapter 4 comprises of field trials conducted in the southern Cape of South Africa. The trials evaluated two different types of disc planters and various crop residue on wheat, barley and canola production. This chapter was written with the intention of publishing it as a scientific article in a peer-reviewed journal.

Chapter 5 consists of a decomposition trial conducted in the field. Different decomposer communities and various crop residue types was evaluated in the decomposition process. The abovementioned factors are discussed in terms of their influence on the rate of decomposition. This chapter was submitted to Crop Science. The article can be cited as follow: Kotzé TN, Pieterse PJ, Strauss JA, Swanepoel PA. (s.a.). Decomposition of Different Types of Crop Residue in Response to Soil Faunal Decomposer Communities. Crop Science (under review).

Chapter 6 consists of the general conclusion and recommendations drawn from all the chapters. Limitations and future research are also discussed in this chapter.

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Chapter 2: The effects of crop residue on barley, canola and wheat yield: A meta-analysis of field trials

TN Kotzé, PJ Pieterse, JA Strauss, PA Swanepoel

2.1 Introduction

Conservation agriculture (CA) has been defined as a more sustainable cultivation system for the future (Hobbs et al. 2008). The three main principles of CA is; (1) minimum soil disturbance, (2) residue retention and (3) crop diversification (e.g. crop rotation) (Mondal et al. 2019). Benefits of CA include, but is not limited to, increased macro and water stable aggregates and better water infiltration into soil (Mondal et al. 2019). Although no-tillage has a tendency to decrease grain yield, when no-tillage is combined with residue retention and crop rotation (viz. CA) the probability to obtain yield loss drops (Pittelkow et al. 2015; Li et al. 2020). Conservation Agriculture can however result in yield loss in very wet and cold climates (Pittelkow et al. 2015), and its outcome is therefore context-specific (Swanepoel et al. 2018). In spite of possible reduced (or similar) crop yields from CA compared to conventional agriculture, CA is generally more energy efficient (Moradi et al. 2018). Adopting CA practises may not always result in the highest yield, but with fewer inputs overall, the system productivity supports sustainability.

Crop residue retention is an important factor to ensure sustainable production and has multiple benefits. Retaining crop residue is beneficial in areas where rainfall is low or sporadic as it promotes moisture conservation and may consequently increase yield (Calzarano et al. 2018). Residue retention is therefore an important practise considering the expected reduced rainfall due to climate change in various cropping regions (Midgley et al. 2005; Hewitson and Crane 2006). Furthermore, erosion is limited when retaining residue and practising no-tillage (dos Santos et al. 1993). Residue retention supports the circulation of nutrients, particularly crop residues with a low C:N ratio as it decomposes faster to release nutrients (Calzarano et al. 2018). Nutrient cycling, mediated by soil biota, is a key process in soil and is underpinned by residue decomposition (Carlesso et al. 2019). As soil biota provides additional agroecosystem services, using crop residue to support soil biota could be an effective tactic.

Residue retention does not come without its challenges, the residue may negatively interact with the following crop. For instance, Bruce et al. (2005) reported that retaining a large amount (> 5000 kg ha^{-1}) of wheat (*Triticum aestivum*) residue resulted in reduced canola (*Brassica napus*) yield. Crop residue effects in a crop rotation system is complex as different crops react differently to particular types of crop residue (Ferreira and Reinhardt 2010). For example, when including sorghum (*Sorghum bicolor*) in a rotation, other crops often experiences a yield penalty (Roth et al. 2000). Planting barley (*Hordeum vulgare*) into alfalfa (*Medicago sativa*) residue may also lead to a yield penalty (Ferreira and Reinhardt 2010). The mechanisms of yield penalty effects may be biochemically or physically. Allelochemicals may be released from residue and have phytotoxic effects on subsequent crops (Bruce et al. 2005; Roth et al. 2000; Ferreira and Reinhardt 2010). Canola establishment was reduced when canola seed was placed near wheat residue (Morris et al. 2009). The effects was primarily attributed to physical effects, but the authors include the possibility that allelopathy may play a role. Wheat residue is well known to contain water-soluble phytotoxins that inhibits the growth of wheat and other crops (Alsaadawi 2001). Wheat and barley contain hydroxamic acids such as 2,4-dihydroxy-1,4-benzoxazin-3-one (DIBOA) and 2,4-dihydroxy-7-methoxy-1,4-benzoxazin-3-one (DIMBOA) of which the effects on membranes are not fully known (Weston and Duke 2003). Brassica species are known to contain thiocyanates which can lead to cyanide poising (Weston and Duke 2003). However small amounts of allelochemicals can promote crop growth, a process known as hormesis (Farooq et al. 2013). Retaining a low to moderate amount of residue may release a low amount of allelochemicals which may promote crop growth.

Residue can influence soil processes thus resulting in indirect effects on the subsequent crop. The way crop residue is managed will largely determine the effects experienced. Incorporating residue into the soil may affect production of the crop planted into the incorporated residue as a result of various soil processes such as nitrogen (N) immobilisation and possibly allelopathy (Kimber 1973). Reduced N uptake by plants sown into residue with a high C:N ratio may be attributed to inhibition by allelochemicals or N immobilisation (Wu et al. 2001). The yellowing of the above ground plant material may be attributed to an impaired root system which can be caused by biochemical compounds linked to the residue (Purvis 1990). Depending on the C:N ratio of the residue, N may be immobilised specifically when residue with a high C:N ratio is incorporated (Trinsoutrot et al. 2000). When the residue is not incorporated in soil the possibility of N immobilisation in the soil becomes negligible (Ferreira and Reinhardt 2010).

Retaining a large amount of surface residue can lead to implement blockages in turn leading to poor crop establishment and a yield penalty (Morris et al. 2010). Disc seed drills with large enough discs will tend not to get blocked, but in tough (moist) conditions the residue can be pushed into the seed slot (hair pinning) which will decrease seed to soil contact. Large crop residue loads may lead to poor seed placement (dos Santos et al. 1993). Crop residue loads in excess of 5000 kg ha^{-1} may lead to a crop with elongated hypocotyls (Bruce et al. 2005). Expending seed energy resources to penetrate the residue layer may explain the poor early growth associated with retaining large residue loads (Bruce et al. 2005).

Other indirect effects when residue retention is practised include disease pressure and weed management. Residue retention may promote the survival of pathogens (Sturz et al. 1997), particularly when crops are established in residue of that same crop, as reported for wheat by Sturz et al. (1997). However, when practising CA, crop rotation is a key element to decrease disease pressure (Campanella et al. 2020). More diverse crop rotations where more crops are sown before the same crop is sown again results in a longer disease break (dos Santos et al. 1993). Pre-emergence weed management by means of herbicide application can be a problem when a large amount of residue is retained because of poor soil contact (Khalil et al. 2018). However, some herbicides will retain their efficacy when used in residue retained fields (Khalil et al. 2018). Allelochemicals from crop residue has the potential to reduce weed pressure in residue amended fields but has less efficacy when applied alone compared to a 100 % rate of herbicides (Lahmod and Alsaadawi 2014). Applying a moderate residue load and a 50 % herbicide rate resulted in similar yield compared to a full herbicide rate (Lahmod and Alsaadawi 2014). The afore mentioned may potensially result in herbicide resistance.

Temperate crops, such as wheat, barley and canola are commonly grown in rotation. Wheat is a widely cultivated crop and plays a big role in feeding a growing world population, the forecast for the total production of wheat in 2020 is 760.1 million tons (FAO 2020). Conservation agriculture, and more specific residue retention, has many benefits, but also has challenges. Distinguishing between possible causes of the negative effects observed where a large residue load is retained is difficult in the field. A combination of possible causes is probably involved. This paper aims to investigate possible ways to mitigate or minimise the negative effects while retaining residue to preserve the positive effects. To support the aim, a meta-analysis was conducted to further investigate the effects of crop residues on subsequent crop yield and to identify a possible optimum residue load.

2.2 Material and Methods

2.2.1 Data collection

Data was extracted from peer-reviewed articles that forms part of three databases, i.e. the Institute for Scientific Information Web of Science (http://apps.webofknowledge.com), Scopus (https://www-scopus-com) and Cab Abstracts (https://www-cabdirect-org). The databases were searched using the following Boolean equation: (("crop residue" OR "organic mulch" OR "stubble") AND (allelopathy* OR phytotoxic* OR biochem*) AND (wheat OR *triticum* OR barley OR *hordeum* OR canola OR *brassica*)). The databases were adjusted so that the keywords apply to the article topic and not necessarily the title and no further restrictions were placed on the search. The last literature search was conducted on 31 October 2019. The search delivered a combined total of 796 results. The articles were screened to conform to the following criteria: (1) the grain yield must be reported; (2) the full-text articles must be written in English; (3) three or more replications of each treatment (type of residue and/or residue load) must be reported; (4) the test crops must be barley, wheat, canola or rapeseed; (5) the study must be a field trial. Eleven studies which was distributed over five continents, were used for the analyses. The eleven studies consisted of four irrigation studies (34 observations) and seven dryland studies (129 observations).

2.2.2 Data management

Articles that met the abovementioned criteria was further used for data extraction purposes. The mean grain yield was extracted for each treatment as well as the residue load and type of tillage. Additional information such as the study location, irrigation, annual average rainfall, and test crop was also extracted from the studies if available. In studies where data was presented on graphs the values were determined using the WebPlotDigitizer (Rohatgi 2019).

Some studies did not present the exact GPS coordinates, in such cases the coordinates of the nearest town were used to reflect the spatial distribution of the studies (Figure 2.1).

Figure 2.1: The spatial distribution of the trials which was subjected to the data extraction process.

2.2.3 Data categories

The residue load treatments consisted of the previous crop's residue and was categorised as follow: Zero residue load treatment (A) 0 kg ha^{-1}; Low residue load treatment (B) 1 to 3000 kg ha^{-1}; Moderate residue load treatment (C) 3001 to 5000 kg ha^{-1}; High residue load treatment (D) more than 5000 kg ha^{-1}. Treatment A reflected fallow fields which were sprayed or ploughed as well as fields where as much as possible of the available residue was removed with only the roots present in the soil at planting. The four irrigation production studies did not contain any low residue load treatment (1-3000 kg ha^{-1}) observations.

Following the primary analyses of the residue load, it was decided to analyse the type of cultivation as well for all the extracted articles. This was done to compliment the findings of the study. The type of cultivation was assigned to three groups namely, no-tillage (NT), shallow tillage (ST) and conventional tillage (CT). For cultivation practices to qualify as NT the soil may not have been cultivated prior to seeding and only seed-drills (fitted with either disc or tine-type openers) were used to establish crops. Shallow tillage was defined as one or more cultivations shallower than a depth of 150 mm. Conventional tillage was defined as a mouldboard plough or aggressive cultivation to a depth greater than 150 mm. For the irrigation studies analysis, the NT and ST categories were combined and renamed to reduced tillage (RT) due to the low number of treatment observations in the NT and ST categories.

The study locations climate was grouped according to the Köppen-Geiger classification (Figure 2.2). The classification considers the monthly average temperature and the monthly average rainfall. The Köppen-Geiger classifications for each of the observations was used to get a context of the type of climate under review. The codes beginning with a “D” indicates a cold climate where snow is common in winter, this represents 31.9 % of the total observations. The codes beginning with a “C” and “B” can fall below freezing point (0°C) in winter but do not receive snow as a rule but in exceptional cases it can sometimes snow. The observations classified as an arid or semi-arid climate is the Bsk, BWh and BSh which represents 22.7 % of the total observations.

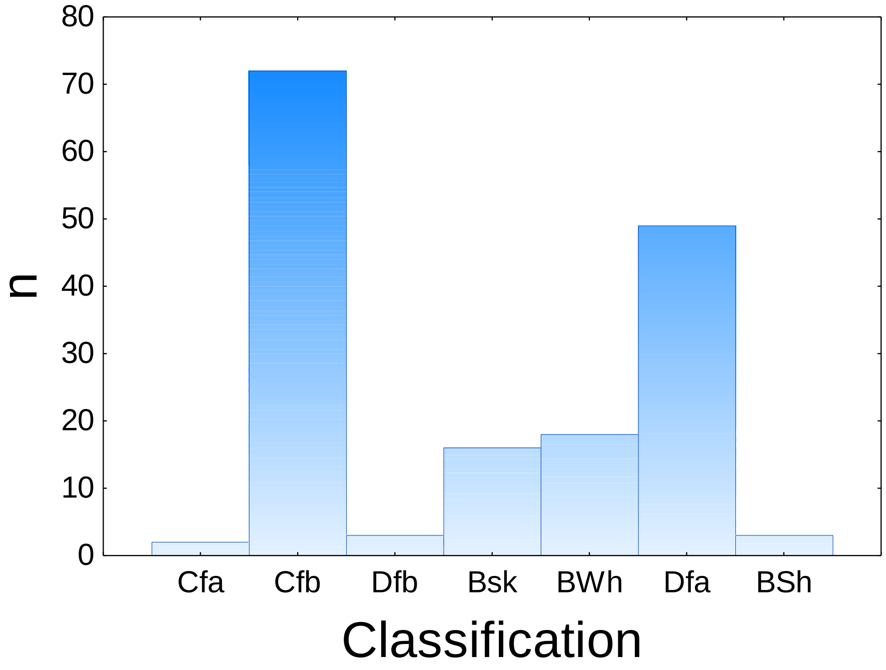

Figure 2.2: The classification of the observations according to the Köppen-Geiger classification. On the Y-axis is the number of observations and on the X-axis the Köppen-Geiger classification. Cfa is a Humid Subtropical climate; Cfb is an Oceanic Climate; Dfb is a Mild Continental Humid climate; Bsk is a Cold Semi-Arid climate; BWh is a Hot Desert climate; Dfa is a Warm Continental Humid climate and lastly BSh is a Hot Semi-Arid climate.

2.2.4 Data analyses

Some of the extracted information was used in forest plots to visually represent the data. The extracted information used for the forest plots include the residue load from the previous crop as well as the tillage practises. The extracted information was then split up according to dryland crop production and irrigation crop production.

2.2.4.1 Forest plots

The forest plots were constructed on the Evidence Partners' Forest Plot Generator (2019) website, as prescribed by (Neyeloff et al. 2012). Firstly, the effect sizes of the grain yield for each crop were calculated.

$$(1)\ Effect\ size = \frac{Mean\ (treatment) - Mean\ (grand\ population)}{Standard\ deviation} \times\ 100$$

Standard error (SE) was calculated for each individual assigned category.

$$(2)\ \ SE = \frac{effect\ size}{\sqrt{effect\ size\ x\ n}}$$

Next the individual study weight was calculated. The larger the SE the smaller the study weight.

$$(3)\ Individual\ study\ weight\ (w) = \frac{1}{SE^2}$$

Following the individual study weight, the study weights was calculated.

$$(4)\ Weight\ (\%) = w \times \frac{1}{\sum Weights}\ \times\ 100$$

The lower (-95%) and upper confidence levels (+95%) were calculated as follow.

$$(5)\ Confidence\ Interval\ (CI) = \overline{X}\ \pm\ Z\ \frac{\alpha}{2}\ \times \frac{\sigma}{\sqrt{n}}$$

All of the abovementioned parameters were calculated and uploaded into the forest plot generator.

2.2.4.2 Statistical analyses

An Analysis of Variance (ANOVA) was conducted to analyse treatment effects between the respective categories. Normality of residuals were tested with the Shapiro-Wilk test, and homogeneity of variances were evaluated with Levene’s test. If residuals were not normally distributed, or when variances were heterogenous, the Games-Howell, Kruskal-Wallis and Mann-Whitney *post-hoc* procedures were used to confirm the results of the ANOVA. The Fisher’s least significant difference test were used to separate treatment means at a 5% significance level. Statistica version 13.5.0.17 was used to conduct statistical analyses (TIBCO Software Inc. 2019).

2.3 Results

2.3.1 Residue load effect on relative yield under dryland

Zero residue (treatment A) resulted in a relative grain yield increase ($p < 0.05$) compared to high residue loads (Figure 2.3). The zero-residue load treatment did however not differ ($p > 0.05$) from the low residue treatment. When residue load was higher than 3000 kg ha^{-1}, the lowest yields were recorded. Although the low residue load treatment had relatively few observations and high variance it did not differ from the moderate and high residue load treatments ($p > 0.05$). Overall, the relative yield decrease due to a higher residue load is relatively small (under 5 %) under dryland conditions.

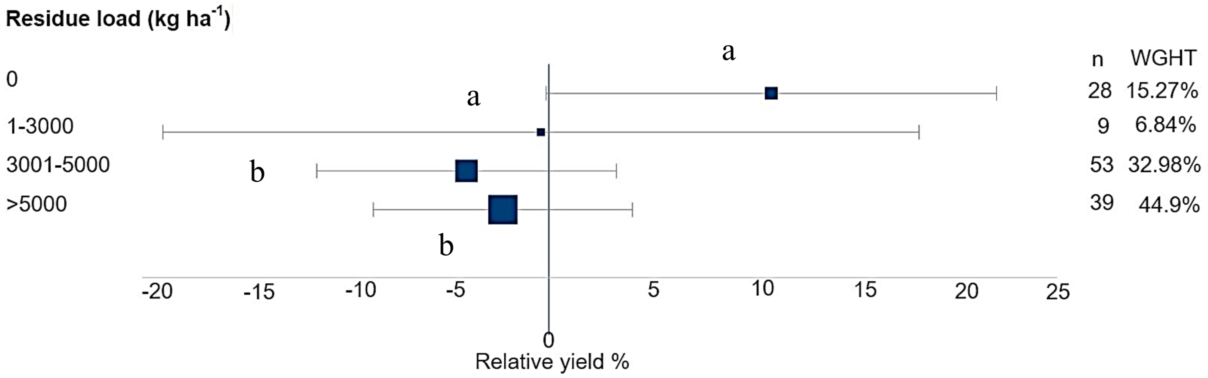

Figure 2.3: The effect of the residue load (kg ha^{-1}) on the relative yield (%) under dryland conditions for wheat, barley and canola. The residue load is on the Y-axis and the relative yield is on the X-axis. The vertical line (0) on the X-axis is taken as the control, the control was taken as the mean of all the combined treatments. No common letters indicate significant difference ($p < 0.05$). On the right-hand Y-axis, n is the number of observations per category and the WGHT represents the individual study weight (%). The larger the SE the smaller the individual study weight (%).

2.3.2 Residue load effect on relative yield under irrigation

Following the zero-residue load treatment a relative yield increase could be expected (Figure 2.4). The zero-residue load treatment did not differ from the moderate residue load treatment ($p > 0.05$). The high residue load treatment resulted in the lowest yield which was significantly smaller than the zero-residue treatment (p < 0.05). The high residue load did however not differ from the moderate residue load (p > 0.05).

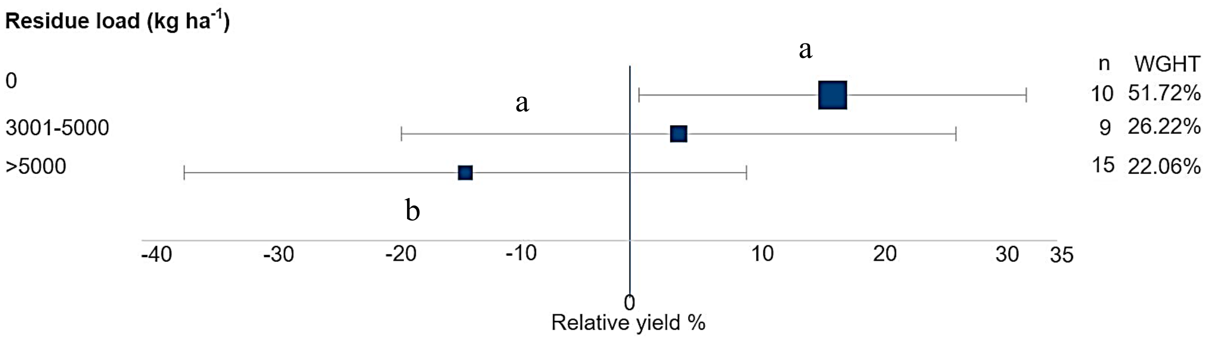

Figure 2.4: The effect of residue load (kg ha^{-1}) on the relative yield of wheat (%) under irrigation practises. The residue load is on the Y-axis and the relative yield is on the X-axis. The vertical line (0) on the X-axis is taken as the control, the control was taken as the mean of all the combined treatments. No significant letters indicate significant difference (p < 0.05). On the right-hand Y-axis, n is the number of observations per category and the WGHT represents the individual study weight (%). The larger the SE the smaller the individual study weight (%).

2.3.3 Cultivation practises effect on relative yield under dryland

The shallow tillage and the no-tillage treatments did not differ from each other (p > 0.05) (Figure 2.5). The conventional tillage treatment differed from the NT and ST treatments (p < 0.05). When following ST or NT a slight relative yield increase could be expected, however the CT treatment led to a slight relative yield decrease. Under the circumstances of this study, it was beneficial to reduce the amount of soil disturbance under dryland conditions.

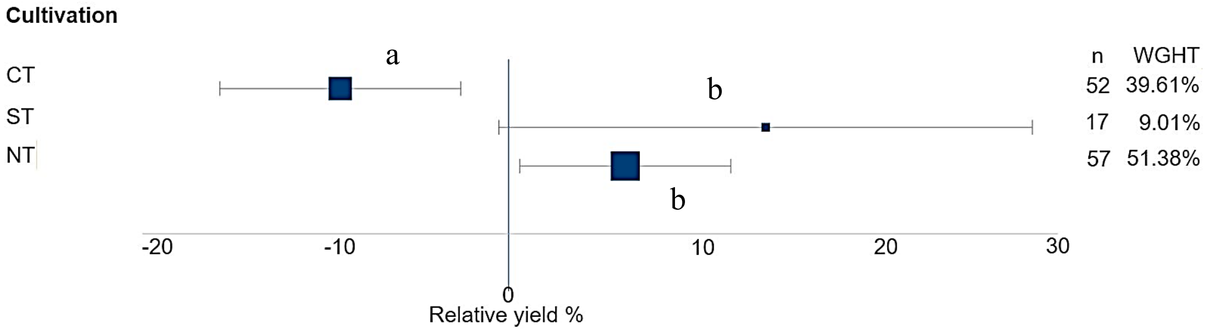

Figure 2.5: The effects of cultivation practises on the relative yield (%) of wheat, barley and canola under dryland conditions. Conservation tillage (CT), Shallow tillage (ST) and No tillage (NT) are on the Y-axis. The relative yield is indicated on the X-axis, with the vertical line (0) point being the control. The control was taken to be the mean of all the treatments combined for each crop. No common letters indicate significant difference ($p < 0.05$). On the right-hand Y-axis, n is the number of observations per category and the WGHT represents the individual study weight (%). The larger the SE the smaller the individual study weight (%).

2.3.4 Cultivation practises effect on relative yield under irrigation

The conventional tillage treatment differed from the reduced tillage treatment ($p < 0.05$) (Figure 2.6). The relative yield increased when following conventional tillage. Although variation was high, and the RT treatment consisted out of a low number of observations the RT treatment led to a large relative yield decrease.

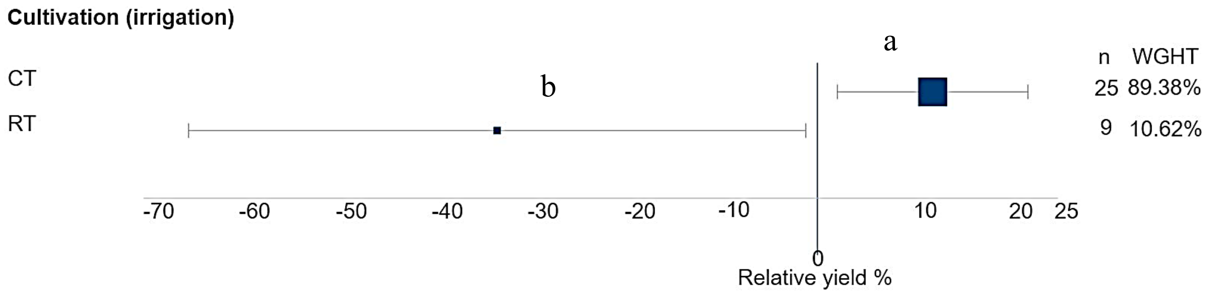

Figure 2.6: The effect of tillage practises on the relative yield (%) of wheat under irrigation practises. Conventional tillage (CT) and reduced tillage (RT) are on the Y-axis. On the X-axis is the relative yield with the vertical line (0) being the control, which was the mean of all the treatments. No common letters indicate significant difference ($p < 0.05$). On the right-hand Y-axis, n is the number of observations per category and the WGHT represents the individual study weight (%). The larger the SE the smaller the individual study weight (%).

2.4 Discussion

Meta-analysis results indicate that retaining high amounts of residues result in yield penalties in both dryland and irrigation production systems. No-till on its own can lead to reduced yields, but when residue is retained in no-tillage systems, yield penalties can be largely prevented (Pittelkow et al. 2015; Li et al. 2020). The complementarities or synergistic effects of adopting the multiple management practices of CA becomes important as complementary biophysical or economic benefits is expected with adoption of multiple CA practices. However, when viewed individually, the retention of high residue loads can lead to yield reductions (Bruce et al. 2005). There can be multiple reasons for crop residues' effects on subsequent crops, such as biochemical, physical, and chemical effects. Although retaining crop residues offers benefits to the physical properties of soil as well as chemical properties (Bhattacharyya et al. 2019), adverse effects of retaining residue such as disease and weed pressure, may also play a role. The negative effects may also have been due to allelochemicals and reduced light penetration through the residue (Bruce et al. 2005). Crop residue from different species has different effects on the subsequent crop, some residue will increase yield while other species might lead to a yield penalty (Ferreira and Reinhardt 2010).

Planning of the rotation sequence is therefore very important especially in cash cropping systems.

In the data gathered in the current study's meta-analysis, the amount of arid and semi-arid observations represents only 22.7% of the total observations. One could argue that if the number of observations in arid and semi-arid environments were more, a moderate or high residue load would have caused no yield penalty (Figure 2.3). Production in dry climate zones will have less of a yield penalty and more of a yield advantage under a higher residue load compared to wetter climates - this can be attributed to moisture conservation (Bruce et al. 2005). The higher moisture levels later in season when conserving residue will likely offset the initial negative effect (Bruce et al. 2005).

The (bio-) chemical interaction amongst plants including those mediated by microorganisms are referred to as allelopathy (Weston and Duke 2003). Crop residue is more inhibitory when fresh residue is compared to weathered crop residue (Purvis 1990; Bruce et al. 2005). A laboratory study showed that the allelopathic effect of crop residue decreases over time even if the residue is stored dry (Mason-Sedun et al. 1986). In regions where only one crop is produced, typical of semi-arid and arid regions, the residue has time to decompose over winter or summer months which may lead to reduced allelopathic potential. The probability to get an inhibitory effect due to allelopathic chemicals being leached from crop residue seems greater with double cropping. Allelochemicals of crops can promote growth if applied at low concentration and will inhibit crop growth when applied at high concentration (Farooq et al. 2013).

In laboratory studies the inhibitory effects due to allelopathy are generally more pronounced than in the field environment (Lovett and Jessop 1982). Some argue that the concentration of allelopathic compounds used in laboratory studies is 20 times higher than found in the field (Morris et al. 2010). The vast volume of soil probably has a big dilution effect on the strength of allelopathic solutions. Microbial breakdown of allelochemicals and adsorption to soil particles under field conditions may also contribute to less allelopathic effects seen in the field compared to controlled environments (Wu et al. 2001). Crop residue decomposition is mediated by soil biota but is also largely dependent on suitable climatic conditions (Carlesso et al. 2019). The rate of decomposition is greater in warm and humid conditions (Arlauskienė et al. 2016).

The quality parameters of residue such as the C:N ratio is an important factor concerning the speed of breakdown as well as causing temporary N immobilisation in the soil when incorporated (Nicolardot et al. 2001). Crops with a high C:N ratio decomposes slower and can cause temporary N immobilisation particularly if the residue is incorporated (Nicolardot et al. 2001). The N uptake of wheat was less when the residue was incorporated compared to when the residue was left on top of the soil (Truong et al. 2019). Some argue that the possible N negative period can be excluded when the residue is not incorporated (Thompson 1992; Ferreira and Reinhardt 2010). In high yielding areas where a lot of biomass is produced, livestock can be used to enhance the decomposition of crop residue as well as the nutrient cycling of residue, however trampling by cattle in very wet areas can cause yield penalties for subsequent crops due to soil compaction (Assmann et al. 2014). Promoting crop decomposition with grazing can be a possible management strategy for reducing the residue load while retaining nutrients compared to when the residue is mechanically removed.

Residue management may also play a role in the effect that residue has on the subsequent crop and soil processes. In a study done on the effects of sunflower (*Helianthus annuus*) residues on winter wheat in Virginia, USA, the incorporation of the sunflower residues led to a yield decrease when compared to the no-till plots (Morris and Parrish 1992). The effects were mainly ascribed to the placement of the sunflower residues in the soil, the authors suspect that sunflower residues have an allelopathic effect on winter wheat (Morris and Parrish 1992). Incorporating sunflower residue led to more pronounced production penalties in comparison with the partial or complete removal of the residue (Babu et al. 2014).

Allelopathy, a possible N negative period and the negative effects that conventional tillage has on the soil structure may explain the slightly negative effect that the conventional tillage had on yield in Figure 2.5. When examining tillage practises associated with the data from the studies included in the meta-analysis, findings are comparable to other studies (Figure 2.5). When no-till is done in combination with the other two practises of CA namely residue retention and crop rotation the probability to obtain yield loss from no-till drops (Pittelkow et al. 2015). In this study there was only 29 observations where the previous crop was the same as the test crop and 38 observations in total did not practise residue retention. In a study done in Scotland, winter barley was seeded into barley residue (Ball and Robertson 1990). The plots where the straw was incorporated at deeper depths performed better when compared to plots where the straw was incorporated at shallow depths. No-till was not done in this study. The reduced yields reported of shallow incorporation was ascribed to waterlogging as well as residue phytotoxicity (Ball and Robertson 1990). The authors did not list disease as a possible cause. Conventional tillage will help reduce disease pressure in a monoculture compared to reduced tillage or no-tillage which leaves the residue on or near the soil surface (Hiel et al. 2016). This again highlights the importance of crop rotation. Under very wet and cold climates conventional tillage can lead to the soil warming quicker which is beneficial for planting the next crop (Daigh et al. 2018). No-till practises can reduce yield when conducted under wet and cold conditions (Pittelkow et al. 2015). The observations in this paper were mostly in relatively high rainfall zones (Figure 2.1), however the rainfall distribution is very important. When poor rainfall distribution occurs for example in a Mediterranean climate where the summer is dry and the winter cold and wet, high annual rainfall areas will lead to the crops being water-logged from time to time in some winter months. The in-season rainfall is an important parameter, but unfortunately not enough studies reported it and a representative data set could not be attained.

Retaining high residue loads will likely have a physical impact on the emerging crops together with practical limitations at planting. Canola seeded into wheat residue of 5000 kg ha^{-1} resulted in a 46% reduction in biomass and a 26% yield decrease (Bruce et al. 2006). The cause of the reduced canola production was attributed to the physical effect of the crop residue on the canola (Bruce et al. 2006). Elongated hypocotyls were found when seeded into high residue loads, elongation of hypocotyls is a common reaction to the reduction in photosynthetically active radiation (Bruce et al. 2006). The expenditure of seed energy reserves to emerge through the residue layer likely resulted in reduced energy investment in early leaf and root growth (Bruce et al. 2006). Seeding into a high residue load a yield penalty was experienced which was attributed to poor seed placement (dos Santos et al. 1993). Seed-drill blockages is more likely in long (> 300 mm) unanchored residue compared to short-chopped residue (Baker et al. 2007). Residue can also be pushed into the seed slot rather than being cut when using disc drills resulting in poor seed to soil contact (Morris et al. 2010). The large residue loads (>5000 kg ha^{-1}) found under irrigation practises, due to higher production, may explain the relatively large yield penalty observed in Figure 2.4, this effect was further pronounced due to less water stress compared to dryland production. The conventional tillage led to a yield increase under irrigation (Figure 2.6). The reason for this increase may be since seeds cannot be accurately placed in the soil under a high residue load and water is also not a limiting factor under irrigation production. Moving the residue away from the seed furrow resulted in better yields in canola and barley compared to regular no-tillage. This was done by placing row cleaners in front of the seeding units (Azooz and Arshad 1998). Removing the residue from the furrow will likely mitigate most of the physical effect of the crop residue on the seedlings while maintaining the benefits of residue retention.

Residue retention may increase disease pressure if the appropriate crop rotations is not implemented. In southern Brazil, where the effect of different rotations on barley yield was evaluated, it was found that a longer rotation system with less barley performed better than a barley-soybean rotation and it was attributed to the effect to a longer disease break (dos Santos et al. 1993). Retaining a lot of residue on the surface provides material for crop diseases to survive in which can lead to yield penalties if the crop rotation sequence is not long and diverse enough (Bajwa 2014). Conventional tillage will help reduce disease pressure in a monoculture compared to reduced tillage or no-tillage, which leaves the residue on or near the soil surface (Hiel et al. 2016). The planning of crop rotation sequences is of great importance to minimise disease pressure. Appropriate rotation sequences, crop resistance and effective spray programs are however effective to manage disease pressure to prevent major yield penalties (Aboukhaddour et al. 2020).

Weed management under CA practises excludes almost all mechanical control methods such as ploughing. Residue retention will have little effect on pre-emergence herbicide efficacy when the correct herbicide is applied as some herbicide types retains its efficacy (Khalil et al. 2018). Pyroxasulfone retained its efficacy in residue retained fields (Khalil et al. 2018). In western Canada cover crops helped to reduce weed pressure and in turn reduced herbicide application as well as reduced erosion in fallow fields (Moyer et al. 1999). Narrow crop rows will help crops compete with weeds (Fahad et al. 2015). Applying sorghum residue together with a 50% rate of mesosulfuron and iodosulfuron reduced weeds significantly (Lahmod and Alsaadawi 2014). Following an integrated approach using different herbicides and agronomic practises, weed pressure is likely to be limited thus no major yield loss is likely.

Retaining the correct amount of residue for a certain climatic area will minimise negative effects and, in the process, benefits will be gained. Various studies conducted over different continents showed a positive effect of residue retentions on soil health (Hiel et al. 2016). The burning of residue led to lower gross N mineralisation rates compared to the residue retention plots (Hoyle and Murphy 2006). No-tillage and residue retention in a rice-wheat system in India promoted the microbial activity of the soil when compared to residue removal and conventional tillage (Saikia et al. 2019). The higher microbial biomass may also cause the allelopathic compounds to be broken down quicker. Microbial activity in soils will however take time to increase and will only do so under the correct management practises. No-till plots where residue was retained had a higher residual N in the 0-5 cm topsoil compared to the conventionally tilled plots. The short-term N availability might sometimes be lower due to enhanced N sequestration into long-lived pools (Bhattacharyya et al. 2019). Crop intensification together with no-tillage will result in added C storage in soils, but no-tillage without enough crop residues can lead to severe soil degradation (Govaerts et al. 2009). Crop residues together with no-tillage leads to higher soil moisture compared to conventional tillage practises and removing the residue (Govaerts et al. 2007). Considering the above mentioned, the retention of a low amount to a moderate amount of residue is beneficial. The yield will not be penalised severely, and a possible yield gain can be expected. Over the long term we should expect that a system where residue is retained will be more sustainable with fewer inputs being required. No-till promotes a better soil structure over time compared to conventional tillage, this can lead to improved grain yields (Gupta et al. 2016). Less tillage resulted in better soil structure and infiltration, which lead to wheat yield increases when less irrigation water was applied (Verhulst et al. 2011). Soil organic matter, and more specific the labile fraction of soil organic matter, plays an important role in maintaining soil structure and providing soil nutrients (Six et al. 1998). Non-inversion tillage such as a chisel plow in the Mid-Atlantic region of the USA resulted in higher labile carbon and soil moisture compared to conventional tillage where the soil was inverted using a mouldboard plough (Lewis et al. 2011). Looking at our results under dryland conditions no-tillage together with a low to moderate residue load will likely be beneficial.

2.5 Conclusion

This global meta-analysis was conducted to investigate the mitigation or reduction of possible negative effects of residue retention on the following crops while still retaining the benefits that residue retention offers. Negative effects due to allelopathic influence of residue on the following crop may be very small if not negligible. The vast volume of soil together with the microbial breakdown of the compounds will likely result in negligible allelopathic effects in a production system where the following crop is seeded in the following year. However, under irrigation production or high potential cropping areas where double cropping is viable, the residue is still largely undecomposed and there may be an allelopathic effect. The incorporation of residue may lead to more pronounced negative effects. The incorporation of residue will lead to N immobilisation if residue with a high C:N ratio is incorporated. Nitrogen immobilisation under NT is negligible.

The optimum residue load is different for each climatic production zone, in very wet areas the optimum residue load will be less than in semi-arid and arid environments. Crop residue can be grazed or baled to reduce the load. The negative effect of a large residue load will likely be offset later during the growing season when more moisture is available compared to uncovered soil in dry environments. Seeding into residue with unsuitable seed drills will likely lead to physical impacts from the residue on the crop. Physical impacts such as overshadowing, and the weight of the residue can largely be avoided when the seeding equipment cleans the seed furrow prior to planting. From the data studied it appears that the optimum residue load is around 3000 kg ha^{-1}. Residue loads should be derived from field trials conducted under similar conditions to be more accurate. Rotation sequences should be adequately planned to prevent the seeding of a crop that is sensitive to a high residue load after a crop that produces a lot of biomass.

Other indirect effects of residue retention such as disease pressure can be effectively managed when the principles of CA are followed. Pre emergence weed control can be done effectively with certain chemicals but a more integrated approach concerning the use of residue will be beneficial over the long run. Finally, there is a great need for more metadata to provide better recommendations concerning residue retention.

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Chapter 3: Allelopathic effects of crop residues on germination and early growth of wheat, barley and canola

3.1 Introduction

Residue retention is of importance for moisture conservation, especially in arid and semi-arid production regions (Calzarano *et al.* 2018). Residue retention in association with crop rotation and no-tillage, can improve environmental, agronomic and economic sustainability in relatively dry Mediterranean climates (Calzarano *et al.* 2018). Crop residues provide valuable ecosystem services, such as the improvement of soil health and the reduction of soil erosion (Turmel *et al.* 2015). Retaining crop residue is key for improving physical, chemical and biological properties of soil which in turn may lead to increased crop yields (Turmel *et al.* 2015). Residue retention will minimise or mitigate negative effects associated with implementation of no-tillage (Li *et al.* 2020).

Large amounts of residue (> 5000 kg ha^{-1}) can however result in a yield penalty, but depends on season and site characteristics (Bruce *et al.* 2005). The effect that crop residue has on the subsequent crop may be ascribed to various mechanisms. Yield penalties, a consequence of poor establishment and retarded early crop growth, may be caused by physical effects or biochemical (allelopathic) compounds (Purvis 1990; Bruce *et al.* 2005).

Physical effects such as reduced light penetration, cold temperatures and poor seed placement may lead to reduced yield. Reduced light penetration may result in elongated and weak hypocotyls (Bruce *et al.* 2006). Low temperatures under the residue layer may lead to reduced metabolic rates of seedlings and subsequently slower growth and early development (Porter and Gawith 1999; Bruce *et al.* 2006). Improper depth placement of seed by no-tillage seed-drills can occur in high residue loads which can lead to non-uniform establishment and impaired seed-to-soil contact (dos Santos *et al.* 1993; Morris *et al.* 2010).

Although there is a limited understanding of the allelopathic effects of crop residue on subsequent crop performance, there are reports demonstrating allelopathic effects in controlled conditions (Wynne *et al.* 2019). Allelopathy can be defined as the biochemical interaction among plants including those mediated by microorganisms (Weston and Duke 2003). Reports of reduced yields from field trials in the presence of residue was attributed to allelopathy especially when the residue was incorporated (Lovett and Jessop 1982). Many factors may influence the outcome of allelopathic effects, for instance the crop type, quality of crop residue and the degree of degradation. Soil may also have a dilution effect on the concentration of allelopathic chemicals under field conditions. Degraded crop residue is expected to be less phytotoxic to subsequent crops when compared to undegraded residue (Purvis 1990). For instance, in the southern Cape region of South Africa, crops are harvested by the end of spring (November) and the subsequent crop is planted the following year in autumn (May). This gives the crop residue time to degrade. Despite these above-mentioned factors influencing the phytotoxicity of crop residues, there is a limited understanding of how crop residue affects subsequent crops.

A study was designed to determine the phytotoxicity of different types of crop residue on the performance of wheat (*Triticum aestivum*), barley (*Hordeum vulgare*) and canola (*Brassica napus*). The study was conducted in two parts. Trial I aimed to evaluate crop residue extracts on germination and germination parameters. Trial II aimed to distinguish between physical and allelopathic effects of wheat residue on early growth of wheat, barley and canola under controlled conditions.

3.2 Material and methods

Trial I: Effects of crop residue extracts on germination of wheat, barley and canola

3.2.1 Trial location

The trial was conducted in 2020 at Welgevallen Experimental Farm (33°56’34.0” S 18°51’59.0” E) in Stellenbosch, South Africa. Donor crop residue, derived from crops of the 2019 season, was collected from a field at Tygerhoek Research Farm (34°09’58.3” S 19°54’34.1” E) in May 2020.

3.2.2 Experimental design and treatments

Trial I consisted of three individual experiments, each investigating the crop residue effects on a different test crop: (1) wheat (cv. SST 0117), (2) barley (cv. Hessekwa) and (3) canola (cv. Alpha). The three experiments were each laid out as a randomised block design with five replicated blocks. The treatment factors for the experiments were extracts from six donor crop residue types and the extract strength. The donor crop residue type was residue of wheat, barley, canola, field pea (*Pisum sativum*), annual medic (*Medicago polymorpha*) and oats *(Avena sativa*). The donor crop residue was used to produce extracts with strengths of 0, 1.25, 2.5 and 5 % weight volume^{-1} (% w v^{-1}). The extract was made by soaking the donor crop residue in distilled water for 72 hours. Extracts were kept in the dark to prevent degradation by light. The extract was filtered through 0.22 µm filter units to prevent fungal and bacterial contamination. Twenty seeds were placed in a 90 mm petri dish on 8-12 µm filter paper. Four millilitres of extract was pipetted onto 20 seeds of the test crop in each petri dish. The seeds were germinated for seven days under light/dark conditions of 16 hr/8 hr respectively in an incubator set at a day-night temperature of 30°C/20°C. The incubator was maintained at a high relative humidity, close to 100 % to prevent evaporation of extracts.

3.2.3 Measurements

Seven days after the seeds were placed in the petri dishes, the percentage germination, coleoptile and radicle lengths were determined. The seeds that had a radicle and coleoptile were counted as germinated while the rest were counted as ungerminated. The coleoptile and radicle length of 10 randomly selected seedlings out of the 20 seeds per petri dish was measured. The mean of all 0 % treatments were used as the control and all other measurements was deducted from the control to calculate the difference.

Trial II: The effect of wheat residue on early growth of wheat, barley and canola

3.2.4 Trial location

The trial was conducted in 2019 in a glasshouse at the Welgevallen Experimental Farm (33°56’34.0” S 18°51’59.0” E) located in Stellenbosch, South Africa. The soil was collected from uncultivated land at Tygerhoek (34°09’58.3” S 19°54’34.1” E) near Riviersonderend, South Africa. The uncultivated soil was used to exclude any effects of plant material present in the soil on the trial. The soil is shallow (30-40 cm) and is a highly weathered shale-derived soil (Smith 2014). The soil had a sandy loam texture with a clay content of 25% and had a pH (KCl) of 8.1. Soil analysis were done, and the nutrients were within the recommended thresholds for crop production in the region.

3.2.5 Experimental design and treatments

The trial consisted of three separate experiments, each laid out as a randomised block design. The three experiments consisted of three test crops, i.e. (1) wheat (cv. SST 0127), (2) barley (cv. Hessekwa) and (3) canola (cv. Hyola 559TT) that were planted into wheat (SST 0127) residue. Treatment factors for each experiment were residue treatment (boiled or unboiled) and residue load (0, 2000, 4000, and 8000 kg ha^{-1}). Each treatment combination was replicated four times. The residue treatment consisted of residue being boiled for six hours in water and being regularly rinsed with clean water to extract as much allelochemicals as possible (Wu *et al.* 2001). For the unboiled treatment, residue was used as is from the field. The wheat residue (SST 0127) was collected in May 2019 prior to the planting of the season’s crop.

Ten seeds were planted per pot (diameter 15 cm; height 16 cm) to a depth of 2 cm for barley and wheat and 1 cm for canola. Three weeks after planting, plants were thinned so that each pot had three plants. The trial was conducted at 25°C in a glasshouse. Pots were irrigated twice a week and fertigation was applied to simulate optimal field conditions with no nutrient deficiencies. The pots were irrigated until water started to drain from the bottom of the pots to ensure that all pots received equal amounts of water. The trial was running from 30 May until 16 July 2019.

3.2.6 Data collection

The trial was terminated 47 days after planting. Plant height was noted, as well as the number of tillers per plant for barley and wheat. The plants were dried at 60 °C for 72 hours and then weighed to determine biomass production per plant.

3.2.7 Statistical analyses

Mixed models were used to investigate the treatment effects. For Trial I, the fixed effects were type of donor crop residue, extract strength and the interaction among the donor crop residue type and extract strength. The random effects consisted of block, the block and donor crop residue interaction and the block and extract strength interaction. For Trial II, the fixed effects were residue load and residue treatment and their interaction. The random effects were specified as the block, the block and residue load interaction, as well as the block and residue treatment interaction. For canola (Trial II), the boiled treatment at 8000 kg ha^{-1} is a missing value (error during preparation of treatments) and treated accordingly. A separate statistical analysis was done evaluating the effect of crop residue load only, this analysis contained an 8000 kg ha^{-1} residue load treatment.

Post-hoc pairwise comparisons were calculated using the Bonferroni test which computes contrasts between the least-squares means of each level of factor. Pairwise comparisons were only conducted between levels of factors that were found to be significant ($p < 0.05$) in the ANOVA. Results are displayed in line and column graphs. Data analyses were undertaken in Statistica version 13.5.0.17 (TIBCO 2019). Models were calculated in the package Variance Estimation, Precision and Comparison (VEPAC) using restricted maximum likelihood (REML), where P-values for the significance of each variable were calculated using type III analyses of variance.

3.3 Results

Trial I: Effects of crop residue extracts on germination of wheat, barley and canola

3.3.1 Wheat

Germination percentage of wheat was not affected ($p > 0.05$) by residue, extract strength or their interaction (Table 3.1). The extract strength did however tend ($p = 0.053$) to reduce the percentage germination as the extract strength increased. The mean germination percentage for wheat was 96.4 ± 6.01 (results not shown).

The type of crop residue determined how the coleoptile lengths were influenced by the extract strength, i.e. an interaction ($p < 0.05$) between the type of residue extract and the extract strength (Table 3.1). Barley and wheat residue reduced ($p < 0.05$) the coleoptile length of wheat at all extract strengths and there was no difference ($p > 0.05$) between the extract strengths (Figure 3.1). Oats and canola had no effect on the coleoptile length when a 1.25 % extract was used but inhibited ($p < 0.05$) coleoptile growth at a 5 % extract strength. Pea residue had no effect at any extract strength, while annual medic residue had an erratic effect.

Table 3.1: ANOVA F statistic and *p* values for wheat, barley and canola germination percentage difference from control, coleoptile length difference (mm) from control and radicle length difference (mm) from control in response to residue type and extract strength (w v^{-1} %). Bold is used to illustrate $p < 0.05$

		Germination percentage		**Coleoptile length**		**Radicle length**	
	Variable	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value
Wheat							
	Residue type	2.07	0.112	11.77	**<0.001**	12.09	**<0.001**
	Extract strength	3.42	0.053	19.66	**<0.001**	17.25	**<0.001**
	Interaction	1.43	0.162	7.75	**<0.001**	6.67	**<0.001**
Barley							
	Residue type	4.40	**0.007**	24.76	**<0.001**	14.44	**<0.001**
	Extract strength	0.18	0.905	14.71	**<0.001**	29.27	**<0.001**
	Interaction	1.47	0.146	5.01	**<0.001**	3.82	**<0.001**
Canola							
	Residue type	5.70	**0.002**	0.57	0.720	88.29	**<0.001**
	Extract strength	0.70	0.569	2.93	0.077	4.08	**0.033**
	Interaction	1.65	0.087	1.54	0.119	17.76	**<0.001**

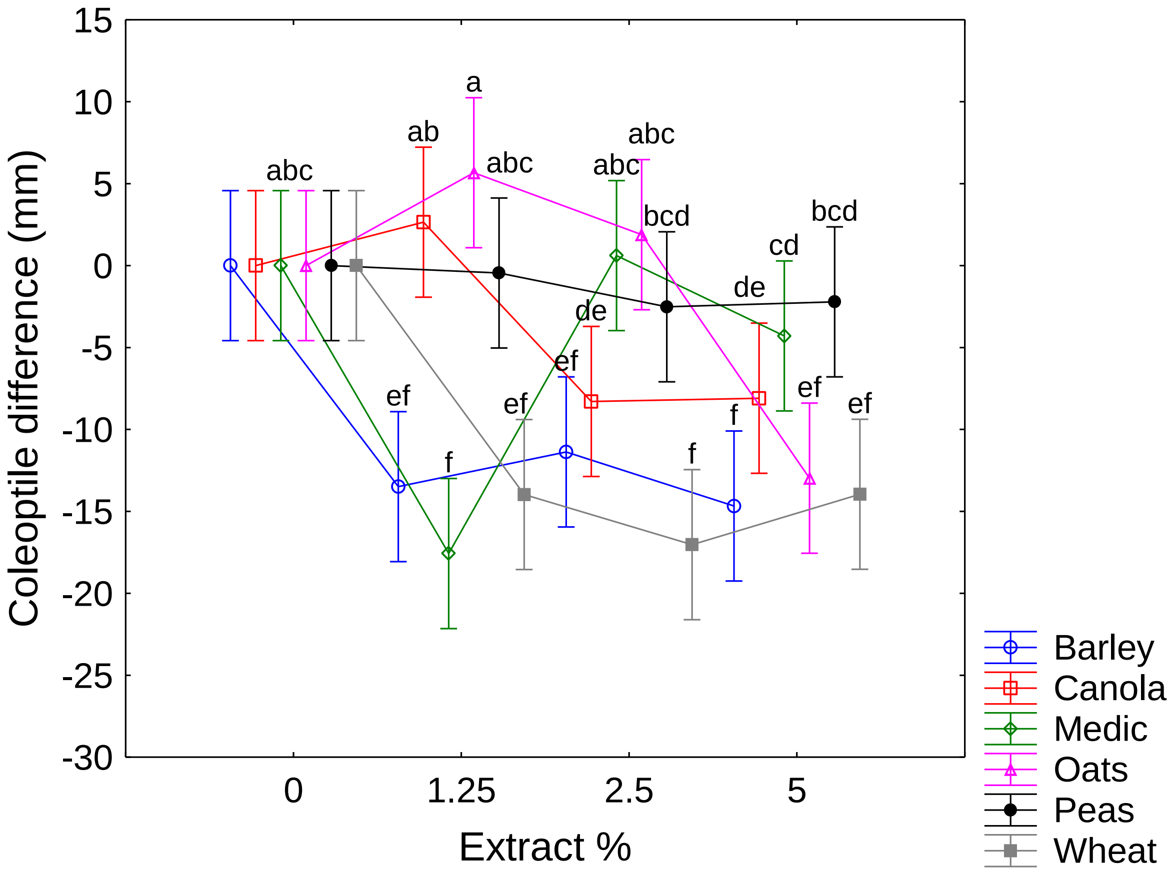

Figure 3.1: The effects of donor crop residue type and extract strength (% w v^{-1}) on the coleoptile length difference (mm) relative to the control of wheat seedlings. Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

The type of crop residue determined how the radicle lengths were influenced by the extract strength (Table 3.1, Figure 3.2). Field pea residue extract strengths did not differ from one another even as the extract strength rose ($p > 0.05$). Oats and canola did not decrease the radicle length when a 1.25 % extract was applied but inhibited radicle growth at 5 % ($p < 0.05$). Barley and wheat residue extract reduced radicle length at 1.25 – 5 % ($p < 0.05$), it seems that the barley and wheat residue is more phytotoxic on wheat compared to the other residues tested.

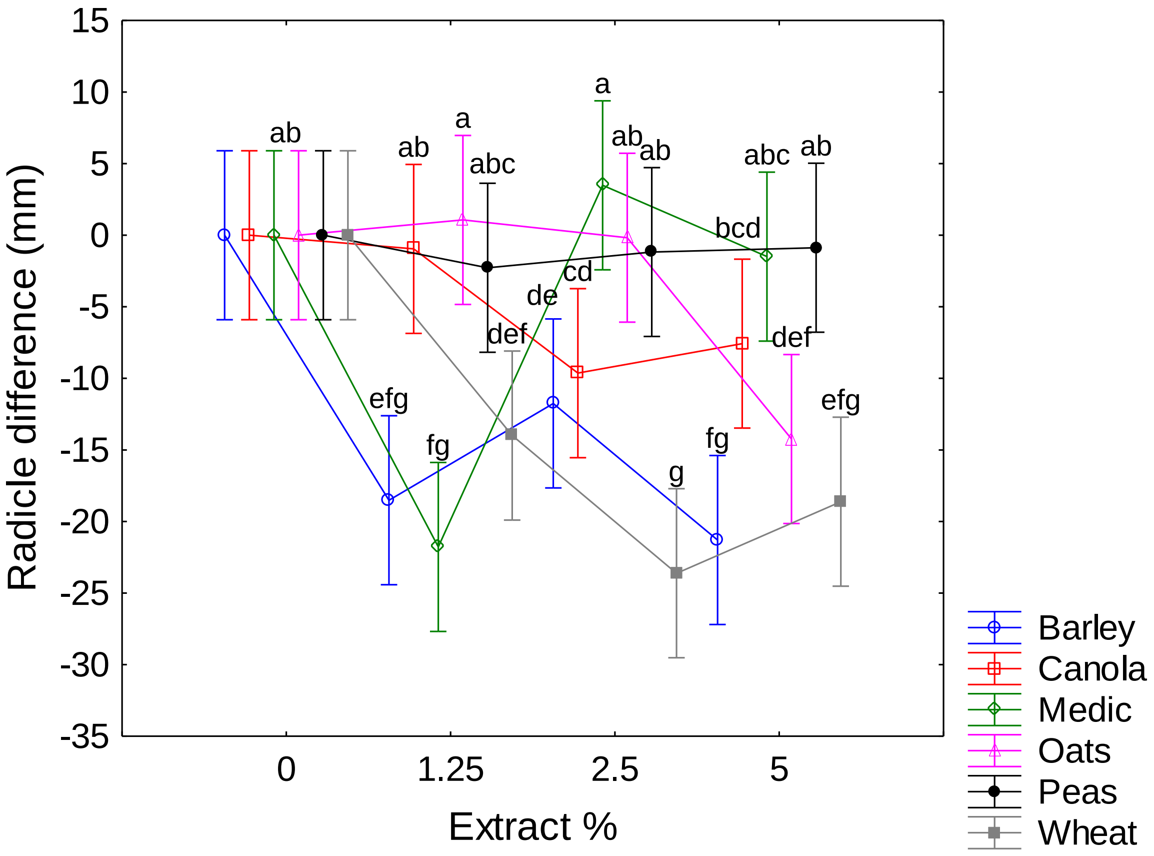

Figure 3.2: The effects of donor crop residue type and extract strength (% w v^{-1}) on the radicle difference (mm) relative to the control of wheat seedlings. Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

3.3.2 Barley

Germination percentage of barley was not affected ($p > 0.05$) by extract strength but was influenced by residue type ($p < 0.05$). There was no interaction ($p > 0.05$) between the treatment factors (Table 3.1). Canola residue resulted in the lowest ($p < 0.05$) germination percentage but was not different to that of oat residue ($p > 0.05$) (Figure 3.3). Annual medic and wheat residue led to an increase in germination percentage of barley ($p < 0.05$). The average germination percentage for barley was 91.17 ± 6.07.

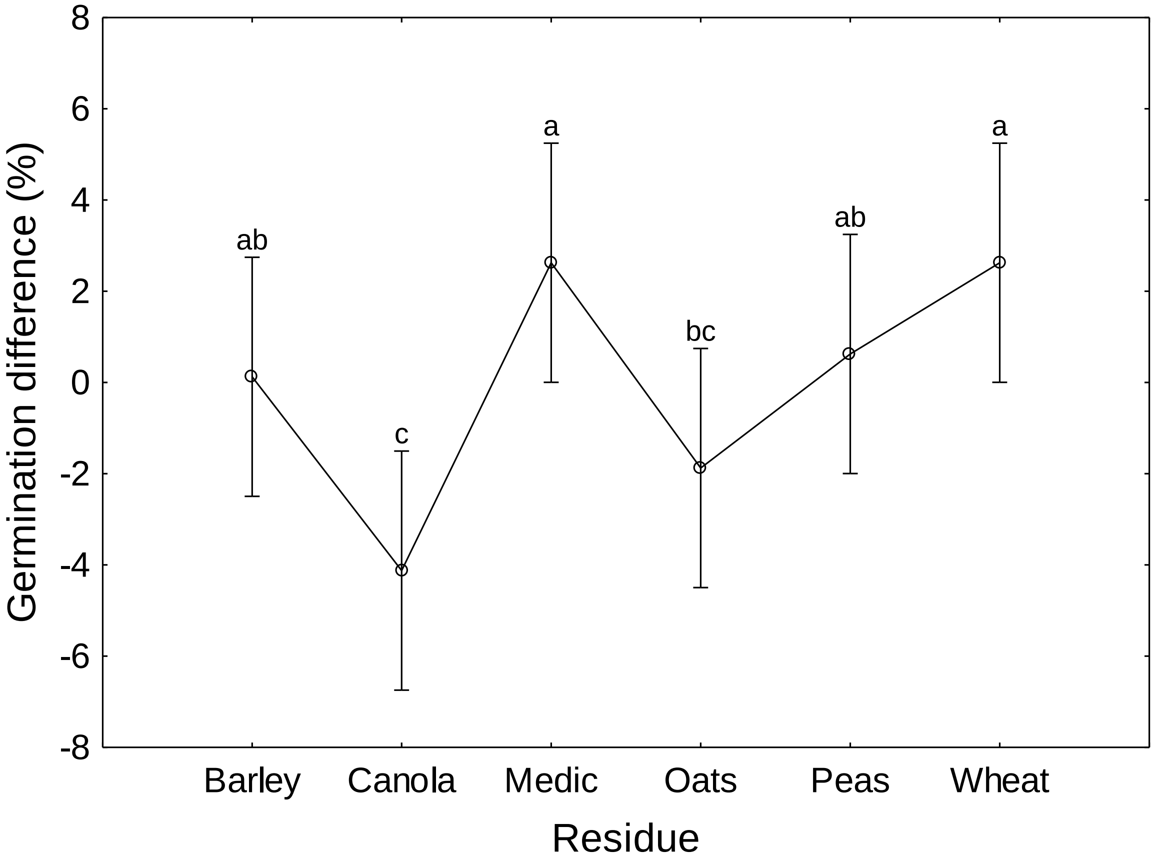

Figure 3.3: The difference of germination percentage relative to the control of barley in response to the donor crop residue type from which the extract was made. Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

The coleoptile length of barley seedlings was influenced ($p < 0.05$) by an interaction between the type of residue extract and the extract strength variables (Table 3.1). Oat residue led to the largest decrease in barley coleoptile length ($p < 0.05$) (Figure 3.4). Canola and pea extracts only led to a decrease in coleoptile length at a 5 % extract strength ($p < 0.05$). The other residue types did however not result in reduced coleoptile lengths ($p > 0.05$). The type of crop residue extract determined how the barley reacted to the extract strength.

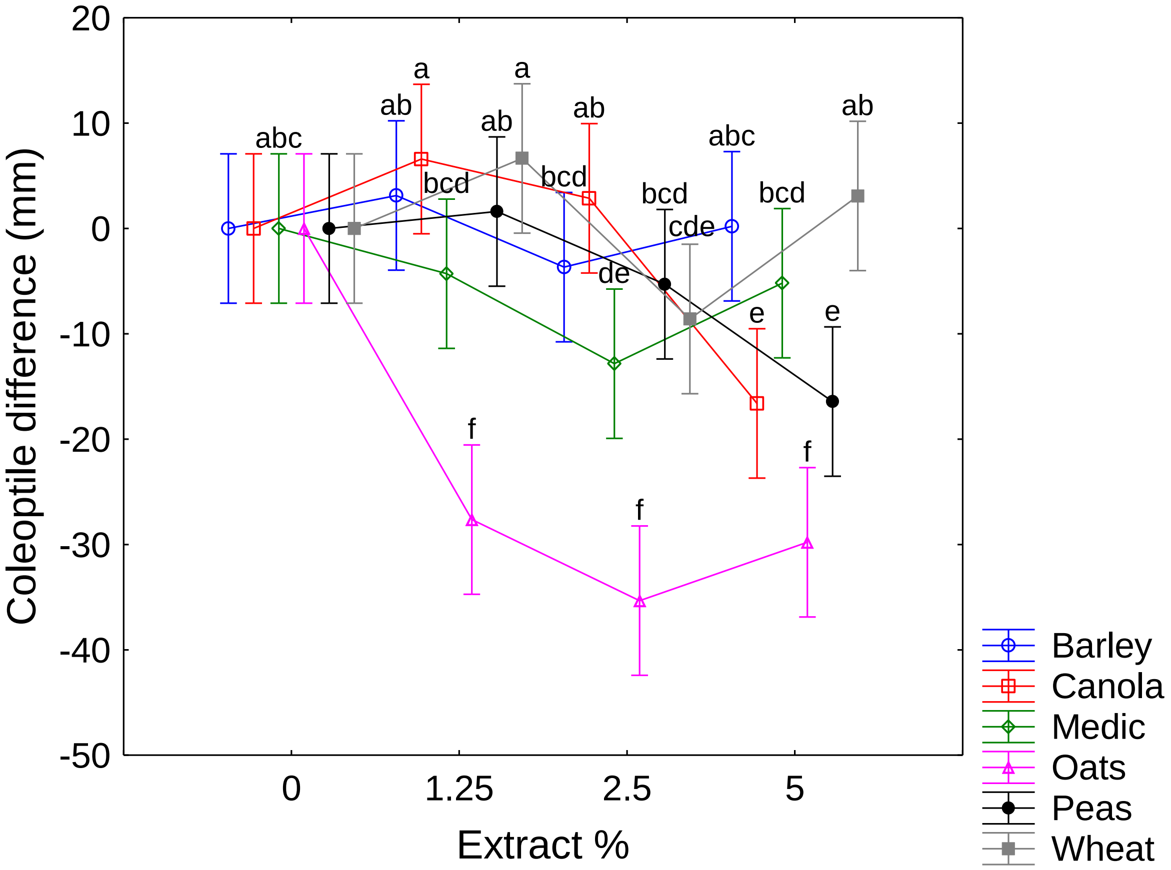

Figure 3.4: The difference in coleoptile length (mm) relative to the control of barley in response to the type of donor crop residue extract and the extract strength (% w v^{-1}). Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

The radicle length of barley was influenced ($p < 0.05$) by an interaction between the residue type and the extract strength (Table 3.1). Oat residue resulted in the largest radicle length reduction at 2.5 % ($p < 0.05$) (Figure 3.5). Wheat, annual medic and barley residue extract did not influence ($p > 0.05$) the radicle length of barley at a 5 %. The type of residue dictated the effect that a specific extract strength had on the barley radicle length.

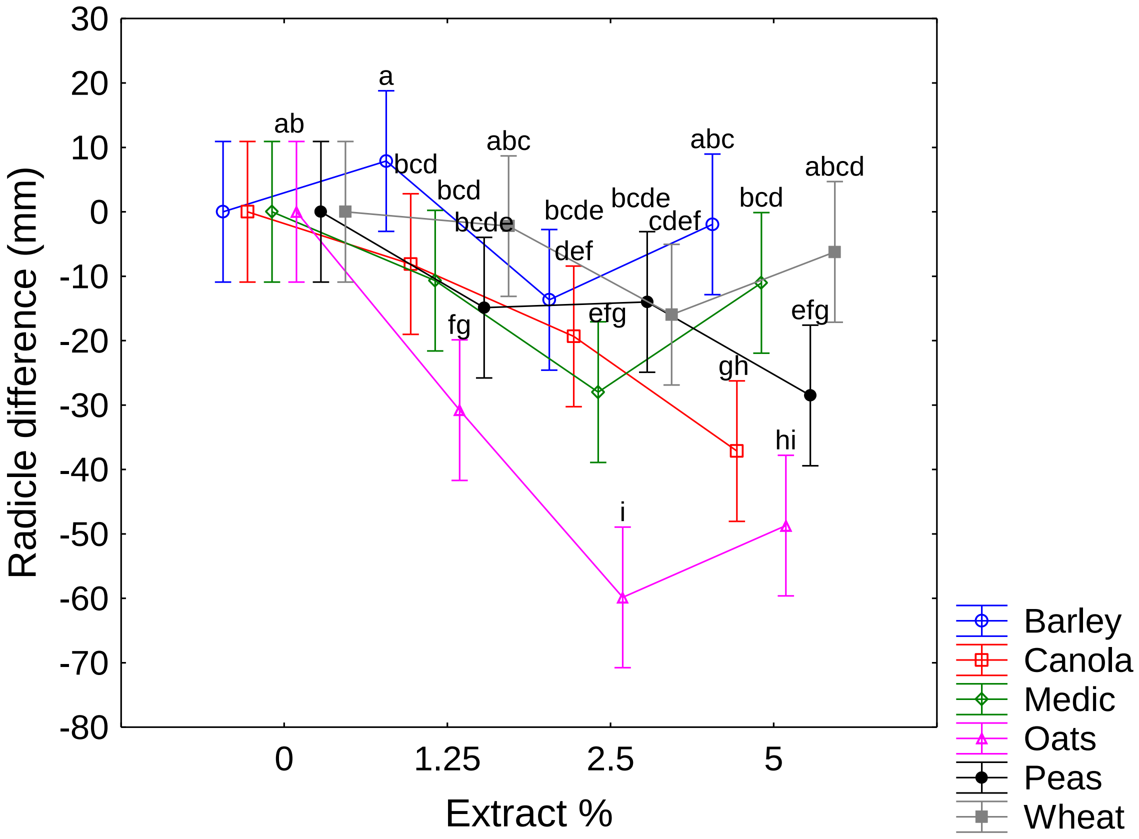

Figure 3.5: The difference in radicle length (mm) relative to the control of barley in response to the type of donor crop residue extract and the extract strength (% w v^{-1}). Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

3.3.3 Canola

Germination percentage of canola was not affected ($p > 0.05$) by extract strength but was influenced by residue type ($p < 0.05$). There was no interaction ($p > 0.05$) between the variables (Table 3.1). Peas and wheat led to the largest germination percentage decrease ($p < 0.05$) (Figure 3.6). Barley residue however led to a slight germination percentage increase ($p < 0.05$). The average germination for canola was 90.38 ± 5.98.

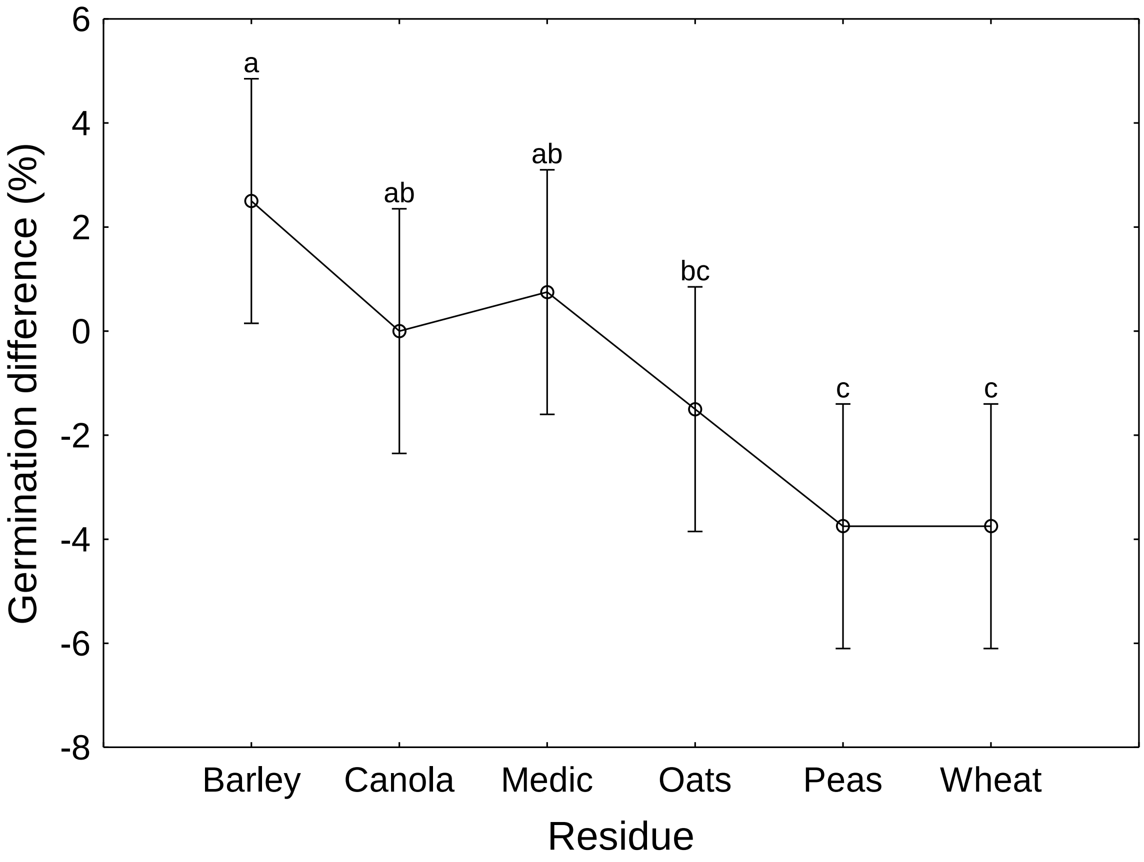

Figure 3.6: The difference in germination percentage (%) relative to the control of canola in response to the donor crop residue type which the extract was made from. Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

The coleoptile length of canola was not influenced ($p > 0.05$) by the type of residue, extract strength or their interaction (Table 3.1). The extract strength at 5 % had a tendency ($p = 0.077$) to promote the coleoptile length of canola. The mean coleoptile length was 14.81 mm ± 3.76 (results not shown).

The radicle length of canola was influenced ($p < 0.05$) by an interaction between the type of residue extract and the extract strength (Table 3.1). The type of residue extract determined how the canola reacted to the different extract strengths. Annual medic residue resulted in a radicle length increase as the extract strength increased ($p < 0.05$) (Figure 3.7). Pea, oat and canola residue resulted in a significant ($p < 0.05$) decrease in radicle length at all extract strengths ($p < 0.05$). Wheat and barley residue had no effect on the canola radicle length ($p > 0.05$).

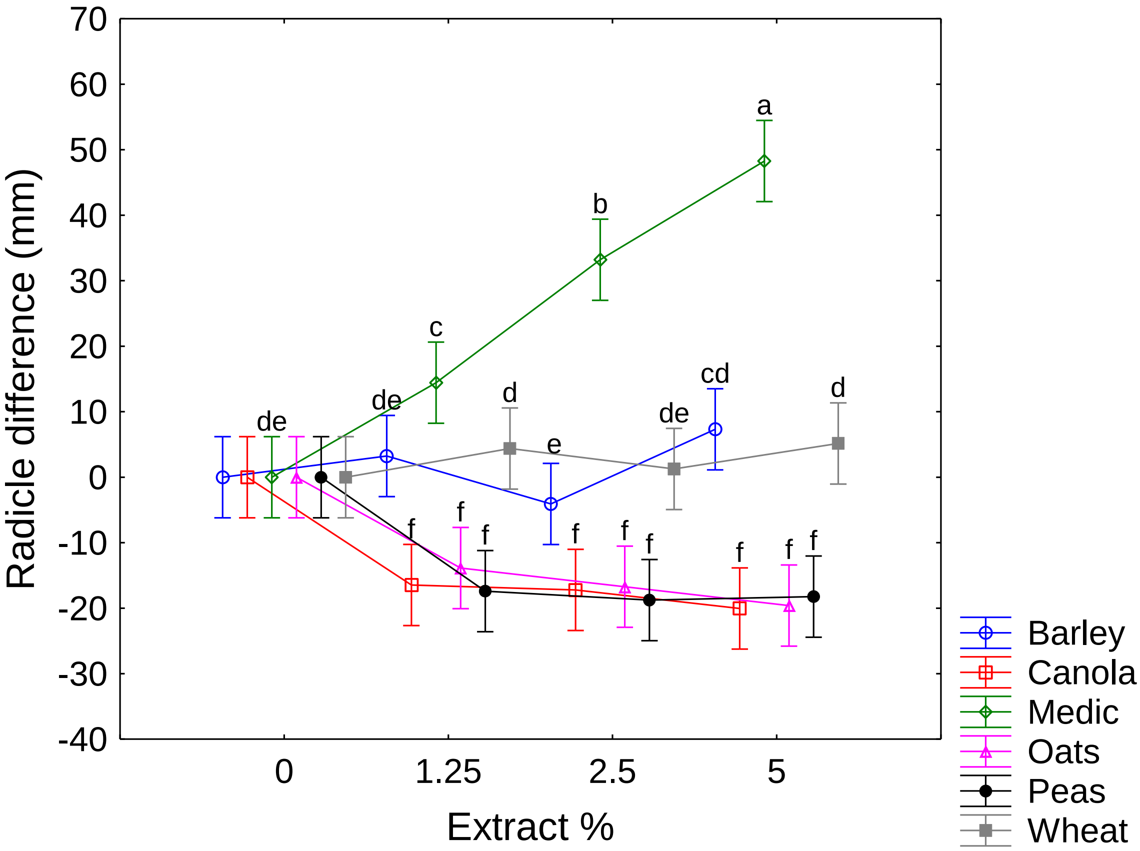

Figure 3.7: The difference relative to the control in canola radicle lengths (mm) in response to donor crop residue type and extract strengths (% w v^{-1}). Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

Trial II: The effect of wheat residue on early growth of wheat, barley and canola

3.3.4 Wheat

The number of tillers per wheat plant was not influenced ($p > 0.05$) by the residue load, residue treatment or their interaction (Table 3.2). The number of tillers of wheat was 1.29 ± 1.64 (results not shown).

Table 3.2: ANOVA F statistics and *p* values for the models of number of side tillers, height per plant and biomass per plant for wheat in response to residue load and residue treatment. Bold is used to illustrate $p < 0.05$

	Tillers		Height		Biomass	
Variable	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value
Wheat						
Residue load	0.37	0.777	1.66	0.245	1.03	0.424
Residue treatment	0.02	0.900	0.38	0.584	0.28	0.636
Interaction	0.62	0.617	0.21	0.886	0.31	0.819
Barley						
Residue load	2.02	0.181	6.23	**0.014**	3.01	0.087
Residue treatment	3.91	0.142	2.51	0.211	3.74	0.148
Interaction	1.91	0.206	3.97	0.053	0.67	0.594
Canola						
Residue load	-	-	0.28	0.762	1.73	0.255
Residue treatment	-	-	1.68	0.285	4.27	0.131
Interaction	-	-	2.66	0.149	8.23	**0.019**

The height per wheat plant was not influenced ($p > 0.05$) by residue load, residue treatment or their interaction (Table 3.2). The height of the wheat was 17.10 cm ± 12.51 (results not shown). The biomass per wheat plant was not influenced ($p > 0.05$) by residue load, residue treatment or their interaction (Table 3.2). The mean biomass per wheat plant was 0.18 g ± 0.27 (results not shown).

3.3.5 Barley

The number of tillers per barley plant was not influenced ($p > 0.05$) by residue load, residue treatment or their interaction (Table 3.2). The mean number of tillers per plant was 1.61 ± 1.77 (results not shown).

Height of barley plants were influenced ($p < 0.05$) by residue load but not by residue treatment (Table 3.2). There was no interaction ($p > 0.05$) between the residue treatment and the residue load. The most elongated plants were under a residue load of 8000 kg ha^{-1} ($p < 0.05$), this was however not different to the plants found under a 2000 kg ha^{-1} load ($p > 0.05$) (Figure 3.8). The shortest plants were found at a 4000 kg ha^{-1} residue load ($p < 0.05$), but was not different to the zero-residue load and the 2000 kg ha^{-1} residue load ($p > 0.05$).

Barley biomass was not influenced ($p > 0.05$) by residue load, residue treatment or their interaction (Table 3.2). There was however a tendency ($p = 0.087$) for the residue load to influence the biomass. Increasing residue load appears to have led to more biomass production. The mean biomass per plant was 0.19 g ± 0.24 (results not shown).

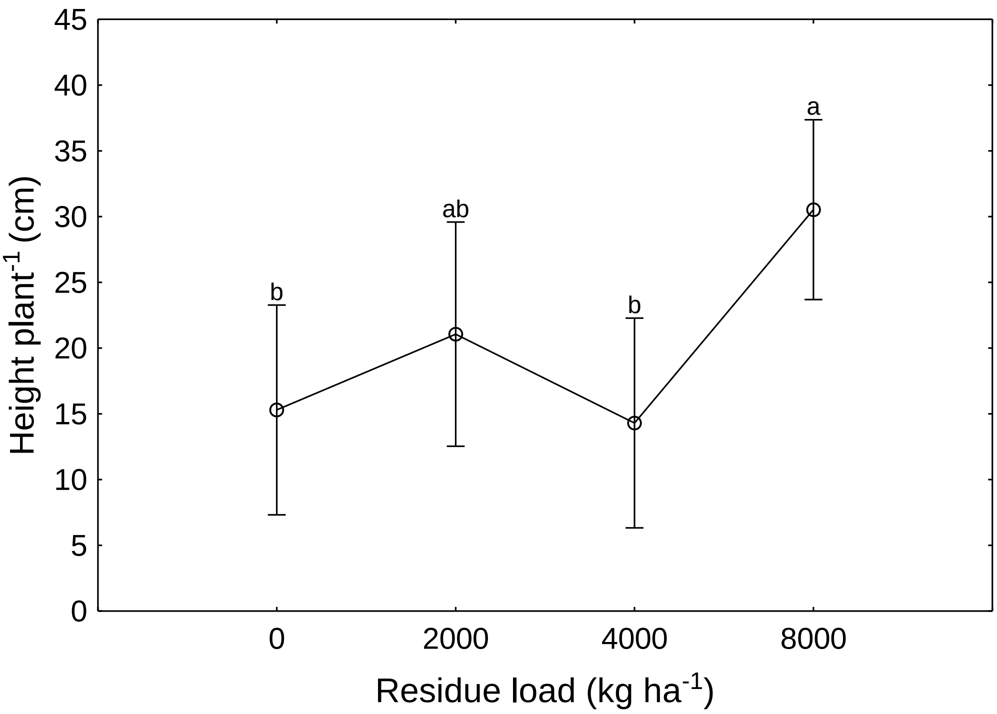

Figure 3.8: The height per barley plant (cm) in response to the donor crop residue load (kg ha^{-1}). Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

3.3.6 Canola

Height of canola was not influenced ($p > 0.05$) by the residue treatment or the residue load (Table 3.2). There was no interaction amongst the variables ($p > 0.05$). The mean height of canola was 9.25 cm ± 5.92 (results not shown). The biomass per canola plant was influenced ($p < 0.05$) by an interaction between the residue treatment and the residue load (Table 3.2). The biomass of canola was similar at residue loads of 0 and 4000 kg ha^{-1} ($p > 0.05$), but at a residue load of 2000 kg ha^{-1}, the boiled residue led to higher ($p < 0.05$) canola biomass compared to unboiled residue (Figure 3.9).

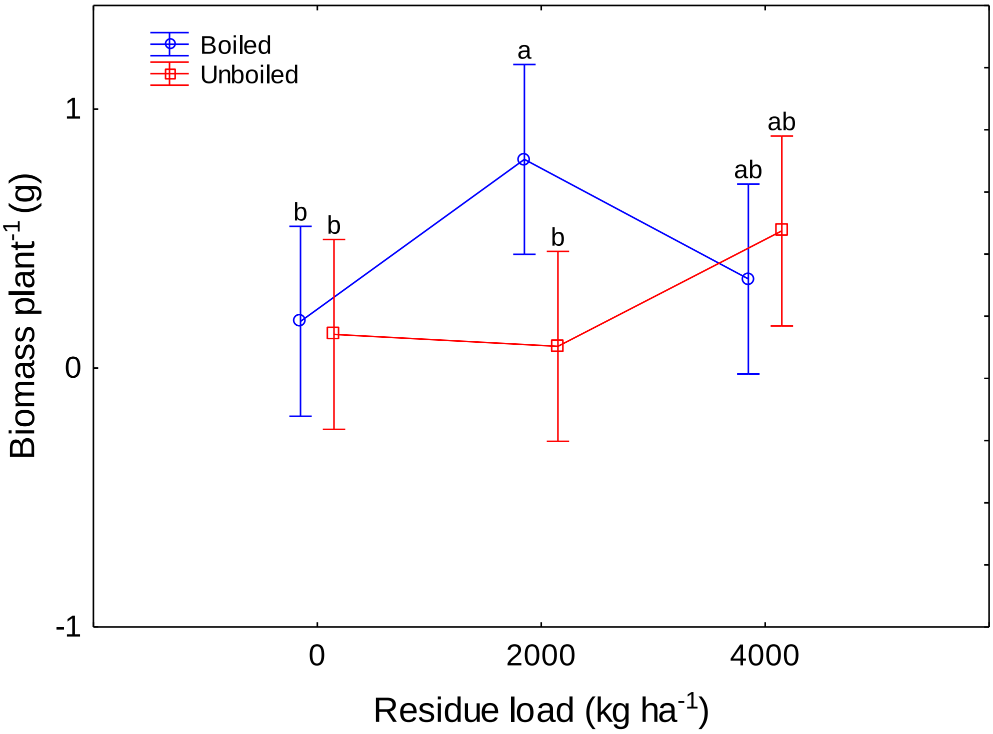

Figure 3.9: The biomass (g) per canola plant in response to donor crop residue load and the residue treatment. Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

When only residue load is considered, the height per canola plant was influenced ($p < 0.05$) by the residue load (Table 3.3). The 8000 kg ha^{-1} residue load led to the shortest canola plants ($p < 0.05$) but was not different ($p > 0.05$) from the zero-residue load and the 4000 kg ha^{-1} residue load (Figure 3.10). The 2000 kg ha^{-1} residue load led to the most elongated plants ($p < 0.05$) but was not different to the zero-residue load and the 4000 kg ha^{-1} residue load. Furthermore, the biomass production per plant was influenced ($p < 0.05$) by the residue load (Table 3.3). The biomass results followed a very similar trend to the height results shown in Figure 3.10. Planting into an 8000 kg ha^{-1} residue load the plants had the least amount of biomass ($p < 0.05$) but was however not different to the zero-residue and the 4000 kg ha^{-1} residue load ($p > 0.05$) (Results not shown). The 2000 kg ha^{-1} led to the highest biomass ($p < 0.05$). Planting into a residue load larger than 4000 kg ha^{-1} did not lead to a further decrease in biomass.

Table 3.3: ANOVA F statistics and *p* values for the models of height per plant and biomass per plant for canola in response to residue load. Bold is used to illustrate $p < 0.05$

	Height		**Biomass**	
Variable	F Statistic	*p* value	F statistic	*p* value
Residue load	3.78	**0.040**	9.89	**0.001**

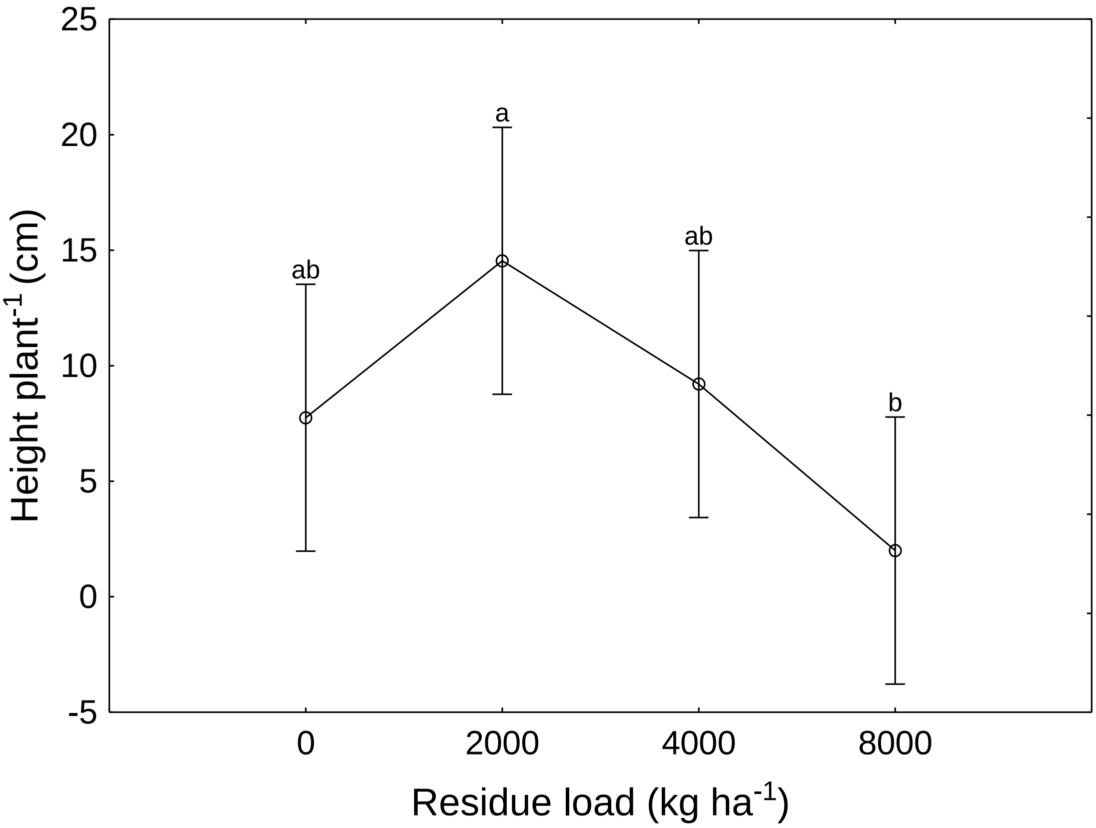

Figure 3.10: The height of canola in response to the donor crop residue load which it was planted into. Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

3.4 Discussion

Crop residue had an influence on the germination as well as the early growth and development of seedlings of the test crops, confirming that allelopathic chemicals must still be present in the residue even after the residue had time to degrade (5 months in field) (Table 3.1). Wheat and barley contain hydroxamic acids which can influence the cell membranes of plants and inhibit cation movement across the membranes (Weston and Duke 2003). Canola residue is known to contain thiocyanates which can in some cases be inhibitory to germinating seeds (Weston and Duke 2003). The effects observed in the germination study may be less pronounced than when fresh residue was used, as the residue used had time to degrade (Purvis 1990). Germination of the test crops was to a lesser extent influenced by the allelopathic compounds when compared to seedling growth parameters (Figures 3.3 and 3.6). The germination inhibition due to donor crop residue extracts is generally small (< 5 %). These findings are similar those of Wynne *et al.* (2019), indicating that seedling growth parameters is impacted more adversely compared to germination by crop residue. Some crops are however more tolerant to the allelochemicals or their growth may even be promoted through means of hormesis at low concentrations (Ferreira and Reinhardt 2010). The wheat, barley and canola seedlings' coleoptile lengths mostly reacted differently to the type of crop residue extract and the extract strength (Figures 3.1, 3.4 and 3.7). The canola coleoptile length was generally slightly stimulated via hormesis by the extracts. The wheat, barley and canola radicle measurements all reacted differently to the various types of crop residue extracts and the extract strengths, indicating that the effects are context-specific (Figures 3.2, 3.5 and 3.7).

In the presence of soil, the allelopathic influence from the wheat residue seemed to decline or even be negligible (Table 3.2). This may be attributed to the fact that the wheat residue was degraded and probably lost some of its allelopathic potential. The adsorption and microbial breakdown of allelochemicals may play a role in the reduced allelopathic activity observed in the presence of soil (Wu *et al.* 2001). These findings are comparable to other studies implying that allelopathy may have a very small or even negligible effect on the following crop (Bruce *et al.* 2006; Wynne *et al.* 2019). Concern has also been raised that a large proportion of allelopathic studies were done in laboratories in the absence of soil (Morris *et al.* 2010). It was suggested that the extracts used in laboratory studies had concentrations 20 times higher than those found in field studies (Morris *et al.* 2010). Our findings indicate that the residue load had a more pronounced effect on the subsequent crop than possible allelopathic effects. This may be different in higher potential cropping areas where double cropping is practical, because in double cropping the crop residue has a lot less time to degrade.

The effects of crop residue on the following crop may be attributed to physical effects and not necessarily allelopathy (Bruce *et al.* 2006; Wynne *et al.* 2019). Physical effects of crop residue on the crop is mainly the overshadowing of seedlings leading to the reduction in photosynthetically active radiation and in some cases low temperatures leading to poor early growth (Bruce *et al.* 2006). The reduction in photosynthetically radiation leads to elongated seedlings (Bruce *et al.* 2006). The physical weight of the residue may also lead to increased energy expenditure of seedlings to penetrate the residue layer and ultimately less reserves is invested into the development of early leaves (Bruce *et al.* 2006). Canola height and biomass production was influenced by the residue load. The larger the seed, the more nutrients it contains which in turn leads to more vigorous early growth (Harker *et al.* 2015; Nik *et al.* 2011). The larger seed size of wheat and barley compared to canola might explain the poor early growth of canola in a high residue load (Figures 3.9). Wheat residue has a poor allelopathic effect on the seedling parameters of canola (Figure 3.7), thus the poor early growth observed is most likely due to physical effects. The physical effects of a large crop residue load on the subsequent crop can largely be mitigated with the use of row cleaners that move crop residue out of the seed furrow (Azooz and Arshad 1998).

Residue management plays an important role in determining the effects on soil processes and the subsequent crop. When the residue is not incorporated, possible nitrogen immobilisation can be excluded (Ferreira and Reinhardt 2010). The incorporation of crop residue in the upper soil layer may lead to detrimental effects (Kruidhof *et al.* 2009). The wheat residue used in the glasshouse was not incorporated but if the residue was incorporated, negative effects may have been observed. Clay dispersion leading to surface crusting is a common occurrence of soils in the region (Amezketa *et al.* 2005; Laker and Nortjé 2019). Thus, the retention of a low to moderate residue load on the soil surface will help to minimize the crusting by softening the impact of the water drops on the soil surface leading to a higher canola biomass.

Height of barley was promoted in the presence of crop residue (Figure 3.8). There was also a tendency for barley to produce more biomass in the presence of a large residue load. Crop residue releases several essential plant nutrients as it decomposes also known as nutrient cycling (Wynne *et al.* 2019). The tendency for barley to grow taller and produce more biomass in the presence of wheat residue may by ascribed to valuable crop nutrients being released from the residue or due to barley being more tolerant to saline soils. The height of canola was the highest at a low residue load and was the shortest in a large residue load (Figure 3.9), in agreement to findings of Swanepoel *et al.* (2019) under field conditions. Although decomposing residue releases several crop nutrients the residue load still has a large influence on the crop, especially if the seed has a low thousand kernel mass.

The accurate placement of seed with good seed to soil contact can be a challenge in large residue loads which may result in yield penalties (dos Santos *et al.* 1993). The wheat and barley did not react to a large residue load, this result may be due to the seed being properly placed at the appropriate depth in the soil prior to the application of the residue. Seed with a higher thousand kernel mass has shown a positive linear association with early biomass (Harker *et al.* 2015). Wheat and barley have a higher thousand kernel mass when compared to the canola, thus the seed may have enough energy reserves to easily penetrate the residue layer and produce its first leaves with proper seed placement.

Although a very high residue load will likely have negative physical effects on the subsequent crop, retaining the appropriate amount of residue for a specific crop and climatic area will be of great benefit. No-till will improve the soil physical properties of soil such as the aggregate size and stability (Li *et al.* 2020). However, improved physical properties of soil will not necessarily lead to an improved yield (Pittelkow *et al.* 2015). Retaining crop residue will mitigate most of the negative effects associated with the adoption of no-till (Li *et al.* 2020). When all three principles of Conservation Agriculture are followed, residue retention, no-tillage and crop diversification the probability to obtain a yield loss from no-till drops (Pittelkow *et al.* 2015). Crop residue is considered one of the most important aspects for improving soil health and supplying nutrients to crops (Gupta *et al.* 2018). The degradation of soils is associated with imbalanced, inadequate and pro-macronutrient fertiliser use together with the inadequate use of crop residue (Gupta *et al.* 2018). Thus, retaining residue and effectively cycling the nutrients may be an effective strategy to reduce our reliance on inorganic fertilizer.

3.5 Conclusion

The crop residue still had an allelopathic potential even after the residue degraded in the field for five months. However, in the presence of soil the allelopathic effects from wheat residue is very small and probably negligible. The effects observed in this study is likely physical in nature and can be mitigated with the use of appropriate implements during the planting process to ensure precise seed placement in high residue loads or that can clean the seed row prior to planting. Canola appears to be more sensitive to a large residue load compared to wheat and barley, likely due to canola having a single radicle and smaller seed size. Planting canola after a crop that produces a low or moderate amount of residue will likely mitigate any negative effects of crop residue.

Although high residue loads might lead to poor early growth in some crops, the correct amount of residue retained for a specific crop is still beneficial. Retaining the appropriate amount of residue will mitigate or eliminate the negative effects associated with large residue loads but will enable producers to retain the benefits from residue retention.

3.6 References

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Chapter 4: Evaluating crop residue effects and disc planter residue handling on wheat, barley and canola production

4.1 Introduction

Conservation Agriculture (CA) may improve environmental, agronomic and economic stability in regions with a relatively dry Mediterranean type climate (Calzarano *et al.* 2018). The three main principles of CA is (1) no tillage, (2) crop diversification and (3) residue retention (Swanepoel *et al.* 2019). The practises of CA promotes water conservation, soil health and prevents soil erosion (dos Santos *et al.* 1993; Hiel *et al.* 2016; Calzarano *et al.* 2018). In Mediterranean-type climates, the rainfall amount and distribution can be very erratic and variable; thus, the adoption of CA may improve the cropping system performance.

Crops react differently to crop residue. Some types of residue might increase the subsequent crops yield while other types may lead to a yield penalty (Ferreira and Reinhardt 2010). The mechanisms responsible for the effects may be physical or (bio)-chemical (Lovett and Jessop 1982; Wynne *et al.* 2019), but is generally not well understood.

Soil chemical, physical and biological processes is influenced by residue retention. When residue has a high carbon-to-nitrogen (C:N) ratio a N immobilisation period, or a so-called N-negative period, can occur and is especially prominent when the residue is incorporated (Nicolardot *et al.* 2001). However, some residue types such as legume residue with low C:N ratios will decompose faster and in turn N will be mineralised quicker which may affect grain yield (Aulakh *et al.* 1991).

When planting into large residue loads, yield penalties may be observed due to physical impacts from the crop residue on the seedlings (Bruce *et al.* 2006). Physical effects may include the physical weight of the residue on the seedlings, overshading and reduced temperatures under the residue layer (Bruce *et al.* 2006). The seed energy reserves required to penetrate the residue layer may lead to slower development of the early leaves (Bruce *et al.* 2006). Reduced soil temperatures under the residue may reduce the metabolic rate of seedlings leading to slower development (Porter and Gawith 1999). Higher soil moisture later in the season may, however, offset the initial reduced early growth in the presence of residue. When the crop residue is removed from the seed furrow negative effects may be alleviated, this can be achieved with row cleaners (Azooz and Arshad 1998). Double-disc planters, for instance, has slightly offset discs which may move more crop residue from the seed furrow compared to the single disc planter.

Certain residue types may have an allelopathic influence on the following crop. Allelopathy can be defined as the (bio-)chemical interaction amongst plants including those mediated by microorganisms (Weston and Duke 2003). The potential of residue to be allelopathic are well-known and has been proven in laboratory trials (Wynne *et al.* 2019). However, in the field, allelochemicals may be transformed or degraded by microbes, or leached, ultimately reducing toxic effects (Wu *et al.* 2001). Degraded residue is less phytotoxic compared to fresh crop residue (Purvis 1990).

In the Western Cape of South Africa, wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), canola (*Brassica napus*), oats (*Avena sativa*), lupin (*Lupinus angustifolius*) and medics (*Medicago polymorpha*) are commonly grown in rotation. Diverse crop rotations therefore exist in the region. However, the effect of the previous crop's residue on the subsequent crop productivity is not well-understood. A better understanding is required to inform farmers of the positive or negative effects of a certain crop's residue on another crop, and optimal crop sequence designs. The aim of this study was to evaluate the effect of different types of crop residue and two types of disc planters on wheat, barley and canola production in the southern Cape of South Africa.

4.2 Material and methods

4.2.1 Study area

The field study was conducted in 2019 (year one) and 2020 (year two) on Tygerhoek Research Farm (19°54˝ E, 34°08˝ S) near Riviersonderend in the Western Cape of South Africa (Figure 4.1). The area has a Mediterranean-type climate with an annual average rainfall of 443 mm and a growing season (April to October) average rainfall of 245 mm. The 2019 total rainfall was below average at 379 mm, however in the first year of the field trial only 117 mm of rain was received within the growing season which made it an extremely dry cropping season. In the second year of the trial 272 mm of rainfall was received in the growing season.

The soil is shallow (30-40 cm) and is a highly weathered shale derived soil. The soil also has a high coarse fragment (Smith 2014). The soil is classified as a sandy loam with a clay content of around 10%. Soil samples were taken prior to the trial and all necessary soil fertility corrections were done in order to ensure that there were no nutrient deficiencies.

Figure 4.1: Aerial view of the crop rotation trials at Tygerhoek.

4.2.2 Experimental design

The research was conducted inside long-term crop rotation trials that was managed under conservation agriculture practises for the past 19 years. Three separate experiments were conducted on three test crops, i.e., wheat, barley and canola, that were planted into various crop residue types. The experiments were laid out as three separate split-plot designs replicated in four blocks. Plot sizes were 12 x 50 m. All experiments had two treatment factors, namely donor crop residue type (whole plot factor) and the type of planter used (sub-plot factor). The planters used were a single disc and a double disc no-tillage planter, which has contrasting residue handling characteristics.

Experiment 1, wheat (year one cv. SST 0127 and year two cv. SST 0117) was sown into the following donor crop residue types: two-year medic, one-year medic, oats, canola and lupin residue. In year two the oats residue was replaced, and wheat was sown into field pea (*Pisum sativum)* residue. This experiment had 40 experimental units.

Experiment 2, barley (cv. Hessekwa) was sown into the following donor crop residue types: two-year medic, one-year medic, oats, canola and lupin residue. This experiment had 32 experimental units.

Experiment 3, canola (cv. Alpha) was sown into the following donor crop residue types: two-year medic, one-year medic, wheat and barley residue. This experiment had 32 experimental units.

4.2.3 Crop establishment and management

Planting in both years were within the optimum planting window, i.e., 10 May 2019 and 13 May 2020. The trial was seeded by an Equalizer single disc planter and an NTX-farm double disc planter. The single disc planter had a row spacing of 203 mm and the double disc planter has a row spacing of 170 mm. The double disc planter (Figure 4.2) moves more crop residue from the seed furrow compared to the single disc planter (Figure 4.3) due to the double disc planter having slightly offset discs. The cleaner seed furrow may reduce the physical effects of crop residue (Figure 4.4).

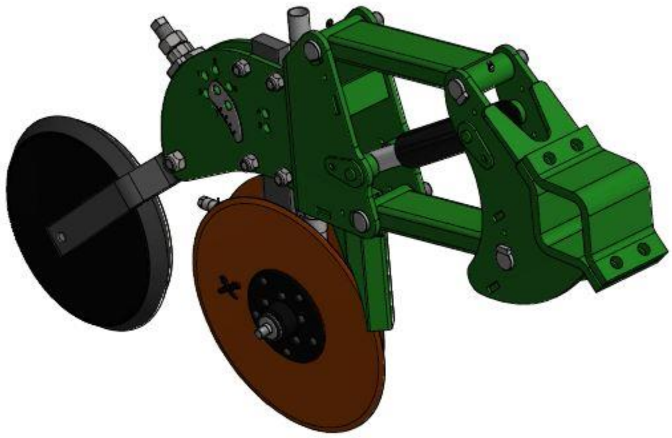

Figure 4.2: The NTX X-farm double disc planter planting unit.

Figure 4.3: The Equalizer single disc planter planting unit.

Figure 4.4: The seedbed after using the double disc planter on the left and the single disc planter on the right.

In both seasons, wheat was seeded at 60 kg ha^{-1}, barley at 50 kg ha^{-1} and canola at 3 kg ha^{-1}. All crops received 6 kg N ha^{-1} in the band. In year one, all crops received a top dressing of 44 kg ha^{-1} N on 3 July 2019. In the second year all crops received a top dressing of 25 kg ha^{-1} N on 24 June 2020.

Weed management was done according to best practise in the area. The crops were harvested on 24 October 2019 and 10 November 2020. All the crops were windrowed 7 days prior to the harvest and harvested using a Claas Dominator 76 combine. The wheat, barley and canola seed yields were standardised to 12, 13 and 8% moisture, respectively.

4.2.4 Measurements

Residue load

Prior to seeding the residue load of the previous year's crop was determined for each plot. This was done by randomly collecting residue from four 0.25 m^2 quadrats per plot. The residue was dried at 60°C for 72 hours and weighed.

Plant population and biomass production

The plant population was determined 20 days after emergence (DAE) by counting plants in 10 randomly selected one-meter rows per plot. The biomass measurements were taken at 30, 60, 90 DAE and at physiological maturity (PM). The measurements were taken by cutting 10 plants at the soil surface and doing a conversion to biomass production per hectare with the plant population.

Soil mineral nitrogen

The mineral nitrogen was determined at 30 DAE and at physiological maturity. One representative soil sample was taken per plot to a depth of 150 mm. The soil samples were analysed in year one for total mineral N using the indophenol-blue (Page *et al.* 1982) and salicylic acid methods (Vendrell and Zupancic 1990) and with the Kjeldahl method in year two (Raveh and Avnimelech 1979).

Yield parameters

Prior to harvesting the number of ear-bearing tillers per square meter was determined for the wheat and barley. The number of ear-bearing tillers were counted in four one-meter rows per plot. The number of spikelets per ear was also determined by counting the number of spikelets on 10 randomly selected ears per plot.

The crops were harvested by picking up a 4.6 m wide row per plot, the length of each row was measured to keep the area harvested constant. Grain quality was determined with a Near-infrared spectroscopy machine at wavelengths between 570–1100 nm. Quality parameters for barley included grain moisture content, protein content, thousand kernel mass (TKM), hectolitre mass (HLM) and kernel plumpness. Wheat quality parameters included grain moisture content, protein content, thousand kernel mass and hectolitre mass. Quality parameters for canola included grain moisture content, oil content and TKM.

4.2.5 Statistical analyses

Mixed models were used to investigate the treatment effects on the crop production. The fixed effects were type of donor crop residue, type of planter and the interaction among the donor crop residue type and planter type. The random effects consisted of block, the block and donor crop residue interaction and the block and planter type interaction. For the mineral nitrogen content analyses the fixed effects were residue type, planter type, sampling date, the interaction between residue type and planter type, the interaction between residue type and date of sampling, the interaction between planter type and date of sampling, the interaction between residue type, planter type and date of sampling. The random effects were specified as the block, the block and residue type interaction, as well as the block and planter type interaction, the block and sampling date interaction, the block, residue type and sampling date interaction, the block, planter type and sampling date interaction. For the donor crop residue load analyses, the fixed effects were specified as crop residue type. The random effects were specified as block and block and crop residue type interaction.

Post-hoc pairwise comparisons were calculated using the Bonferroni test which computes contrasts between the least-squares means of each level of factor. Pairwise comparisons were only conducted between levels of factors that were found to be significant ($p < 0.05$) in the ANOVA. Results are displayed in line and column graphs. Data analyses were undertaken in Statistica version 13.5.0.17 (TIBCO 2019). Models were calculated in the package Variance Estimation, Precision and Comparison (VEPAC) using restricted maximum likelihood (REML), where p-values for the significance of each variable were calculated using type III analyses of variance.

4.3 Results

Experiment 1: Wheat

4.3.1 Donor crop residue load

During year one, the donor crop residue load was influenced (F = 16.38; $p < 0.05$) by the crop residue type. The oats produced the most biomass ($p < 0.05$). The one-year medic pasture led to the lowest residue load ($p < 0.05$) but did however not differ ($p > 0.05$) from the two-year medic, canola and lupin residue load (Table 4.1). During year one, the donor crop residue load was not correlated ($p > 0.05$; $r^2 = 0.032$) with grain yield of wheat (results not shown).

Table 4.1: The crop residue load (kg ha^{-1}) present at the time of planting for both years. No common letters indicate significant difference at a 5% level

Residue type	**Residue load (kg ha^{-1})**
2019	
Two-year medic	2264^b
One-year medic	1592^b
Canola	2360^b
Oats	5705^a
Lupin	2591^b
2020	
Two-year medic	926^b
One-year medic	1652^a
Canola	2153^a
Oats	2185^a
Peas	1070^b

During year two, the donor crop residue load was influenced (F = 10.73; $p < 0.05$) by the crop residue type. The oats residue resulted in the highest residue load ($p < 0.05$) but was not different to the canola residue and the one-year medic residue ($p > 0.05$) (Table 4.1). The two-year medic residue resulted in the lowest residue load but was not different to the pea residue load ($p > 0.05$). During year two, the donor crop residue load was once more not correlated ($p > 0.05$; $r^2 = 0.001$) to the grain yield of wheat (results not shown).

4.3.2 Plant population

Although plant population of wheat in both years was not influenced ($p > 0.05$) by the crop residue type, it was influenced ($p < 0.05$) by the planter type (Table 4.2). There was no interaction between the two treatment factors ($p > 0.05$). The double disc planter resulted in a higher plant population compared to the single disc planter ($p < 0.05$) (results not shown). The mean plant population in year one for the double disc seed planter was 88 plants m^{-2} and 65 plants m^{-2} for the single disc planter ($p < 0.05$). The double disc planter in year two resulted in a mean plant population of 115 plants m^{-2} and the single planter resulted in a mean plant population of 62 plants m^{-2} ($p < 0.05$).

4.3.3 Biomass production

During year one, the biomass of wheat 30 days after emergence was influenced ($p < 0.05$) by the donor crop residue type and the planter type, there was no interaction ($p > 0.05$) between the two variables (Table 4.2). The lupin residue resulted in the highest wheat biomass ($p < 0.05$) while the oats residue resulted in the lowest biomass ($p < 0.05$) (Figure 4.5). The double disc planter resulted in a higher crop biomass compared to the single disc planter ($p < 0.05$) (Figure 4.5).

During year two, the biomass of wheat 30 DAE was not influenced ($p > 0.05$) by the planter type but was influenced ($p < 0.05$) by the donor crop residue type (Table 4.2). There was no interaction between the variables ($p > 0.05$). The canola residue resulted in the highest biomass 30 DAE and the oats residue resulted in the lowest biomass although not significantly different from the rest of the crop residues apart from canola ($p < 0.05$) (Figure 4.5). There was a tendency for the double disc planter to result in higher crop biomass ($p = 0.065$) (results not shown).

During year one, the biomass of wheat 60 DAE was not influenced ($p > 0.05$) by the planter type but was influenced ($p < 0.05$) by the donor crop residue type (Table 4.2). There was no interaction between the two variables ($p > 0.05$). Oat residue led to the lowest wheat biomass while lupin led to the highest wheat biomass ($p < 0.05$) (Figure 4.5).

Table 4.2: ANOVA F statistics and *p*-values for the models of wheat plant population, biomass at 30, 60 and 90 days after emergence (DAE), as well as biomass at physiological maturity, in response to planter type and crop residue type. Bold is used to illustrate *p* values < 0.05

		Plant population		**Biomass 30 DAE**		**Biomass 60 DAE**		**Biomass 90 DAE**		**Biomass maturity**	
	Variable	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value
2019											
	Residue type	0.34	0.847	13.17	**< 0.001**	5.66	**0.008**	4.30	**0.022**	1.42	0.286
	Planter type	26.34	**0.014**	25.37	**0.015**	0.96	0.400	3.92	0.142	2.98	0.183
	Interaction	1.78	0.197	1.43	0.283	0.82	0.537	1.91	0.174	1.64	0.227
2020											
	Residue type	1.74	0.171	4.22	**0.009**	0.97	0.439	0.87	0.495	0.23	0.916
	Planter type	169.52	**<0.001**	3.70	0.065	1.08	0.308	13.02	**0.001**	27.71	**<0.001**
	Interaction	1.36	0.275	0.54	0.708	0.51	0.728	0.60	0.668	2.05	0.116

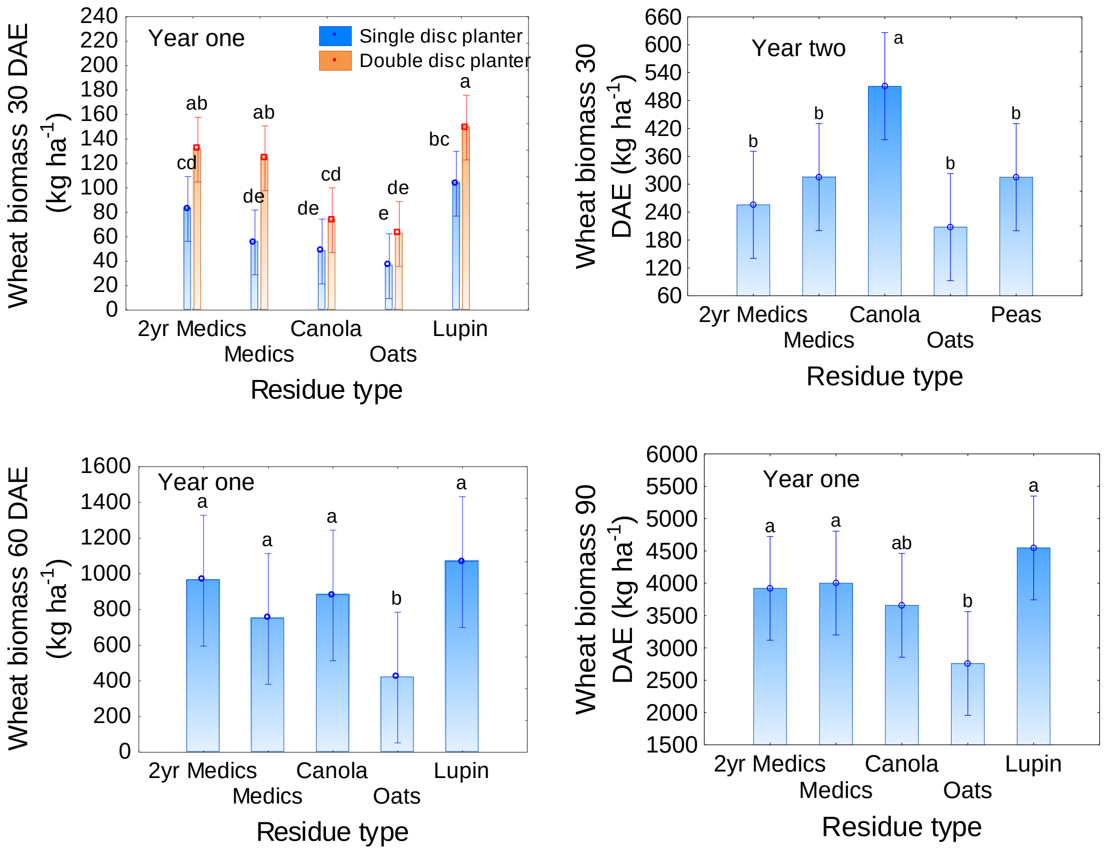

Figure 4.5: The biomass of wheat 30 (year one and two), 60 (year one) and 90 (year one) days after emergence (DAE) in response to the crop residue type and the planter type. Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

During year two, the biomass of wheat 60 DAE was not influenced ($p > 0.05$) by the type of residue type, planter type or their interaction (Table 4.2). The mean biomass was 3775 kg ha^{-1} (results not shown).

During year one, the biomass of wheat 90 DAE was not influenced ($p > 0.05$) by the planter type but was, however, influenced ($p < 0.05$) by the residue type (Table 4.2). There was no interaction between the two variables ($p < 0.05$). The oat residue led to the lowest wheat biomass while the lupin residue led to the highest biomass ($p < 0.05$) (Figure 4.5).

During year two, the biomass of wheat 90 DAE was not influenced ($p > 0.05$) by the residue type but was influenced ($p < 0.05$) by the planter type (Table 4.2). There was no interaction between the variables ($p > 0.05$). The double disc planter led to a higher biomass compared to the single disc planter ($p < 0.05$) (results not shown). The mean biomass in response to the double disc drill was 8931 kg ha^{-1} and the mean biomass in response to the single disc drill was 4150 kg ha^{-1}.

During year one, the biomass of wheat at physiological maturity was not influenced ($p > 0.05$) by the donor crop residue type, the planter type, or their interaction (Table 4.2). The mean biomass was 3695 kg ha^{-1} (results not shown).

During year two, the biomass of wheat at physiological maturity was not influenced ($p > 0.05$) by the donor crop residue type but was influenced ($p < 0.05$) by the planter type (Table 4.2). There was no interaction between the variables. The double disc planter resulted in a mean biomass of 20 612 kg ha^{-1} and the single disc planter resulted in a mean biomass of 12 353 kg ha^{-1} (results not shown)

4.3.4 Yield components, grain yield and quality parameters

During year one, the number of ear-bearing tillers of wheat was not influenced ($p > 0.05$) by the residue type, planter type or their interaction (Table 4.3). The double disc planter did, however, have a tendency ($p = 0.054$) to lead to the development of more ear-bearing tillers. The mean number of ear-bearing tillers of the trial was 133 m^{-2} (results not shown).

During year two, the number of ear-bearing tillers of wheat was not influenced ($p > 0.05$) by the donor crop residue type but was influenced ($p < 0.05$) by the planter type (Table 4.3). There was no interaction amongst the variables ($p > 0.05$). The double disc planter resulted in a mean of 250 ear-bearing tillers m^{-2} and the single disc planter resulted in a mean 218 ear-bearing tillers m^{-2} (results not shown).

Table 4.3: ANOVA F statistics and *p*-values for the models of wheat ear-bearing tillers, spikelets per ear, grain yield, protein content, hectolitre mass and thousand kernel mass in response to planter type and crop residue type. Bold is used to illustrate *p* values < 0.05

		Ear-bearing tillers		**Spikelets**		**Grain yield**		**Protein content**		**Hectolitre mass**		**Thousand kernel mass**	
	Variable	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value
2019													
	Residue type	0.69	0.610	1.15	0.381	1.01	0.441	6.84	**0.004**	13.77	**<0.001**	2.52	0.096
	Planter type	9.56	0.054	0.57	0.507	6.61	0.082	0.53	0.519	29.63	**0.012**	5.72	0.097
	Interaction	1.99	0.160	3.48	**0.042**	0.43	0.782	6.12	**0.006**	2.22	0.128	1.89	0.177
2020													
	Residue type	2.27	0.088	2.01	0.122	6.82	**0.004**	4.11	**0.025**	2.08	0.146	5.14	**0.012**
	Planter type	10.22	**0.004**	0.13	0.724	4.54	0.123	0.42	0.565	4.86	0.115	0.10	0.775
	Interaction	1.66	0.188	1.78	0.161	1.86	0.183	0.48	0.753	1.48	0.268	0.41	0.798

During year one, the number of spikelets per wheat ear was influenced ($p < 0.05$) by an interaction between the residue type and the planter type (Table 4.3). When planting wheat into medic residue, the single disc drill resulted in significantly more spikelets per ear compared to the double disc drill ($p < 0.05$) (Figure 4.6).

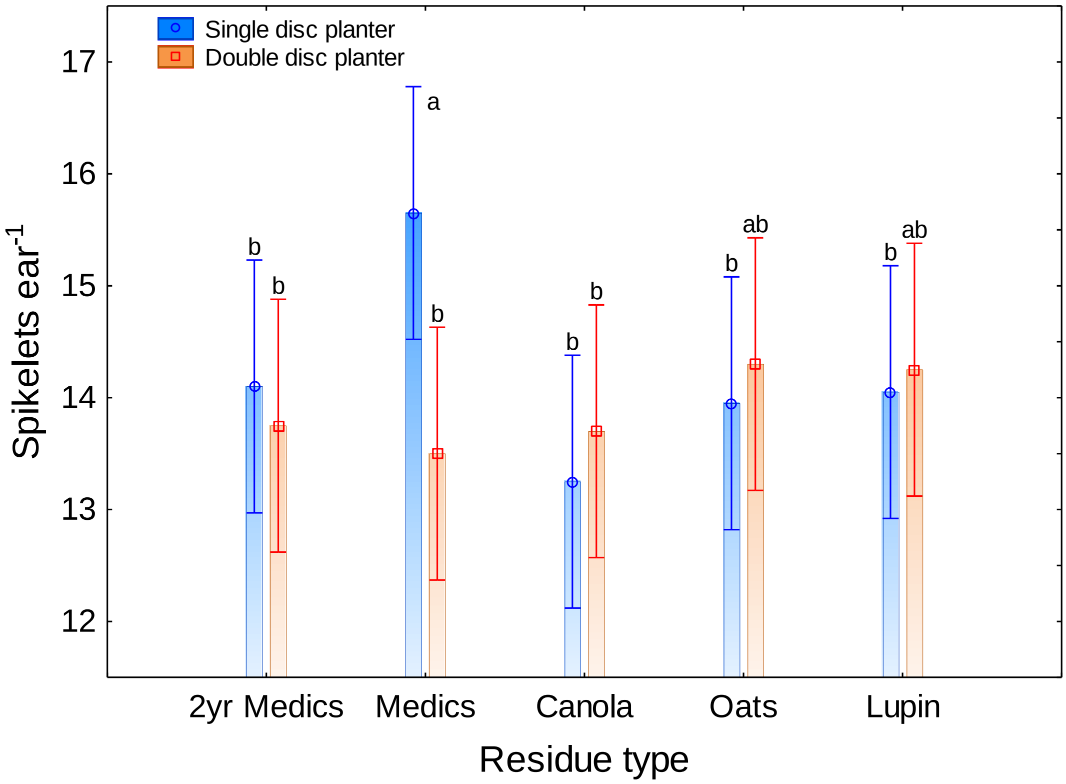

Figure 4.6: In year one, the spikelets per ear of wheat in response to residue type and the type of planter. Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

During year two, the spikelets per ear of wheat was not influenced ($p > 0.05$) by the donor crop residue type, the planter type or their interaction (Table 4.3). The mean number of spikelets per ear was 17.29 (results not shown).

During year one, the grain yield of wheat was not influenced ($p > 0.05$) by the residue type, planter type or their interaction (Table 4.3). There was however a tendency for the double disc drill to result in a higher wheat grain yield when compared to the single disc drill ($p = 0.082$). The mean grain yield for wheat was 1269 kg ha^{-1} (results not shown).

During year two, the grain yield of wheat was not influenced ($p > 0.05$) by the planter type but was influenced ($p < 0.05$) by the crop residue type (Table 4.3). There was no interaction amongst the variables ($p > 0.05$). The oat residue led to the highest wheat yield ($p < 0.05$), but did not differ from the two-year medic residue ($p > 0.05$) (Figure 4.7). The canola residue led to the lowest wheat yield ($p < 0.05$) but was not different to the one-year medic and pea residue ($p > 0.05$).

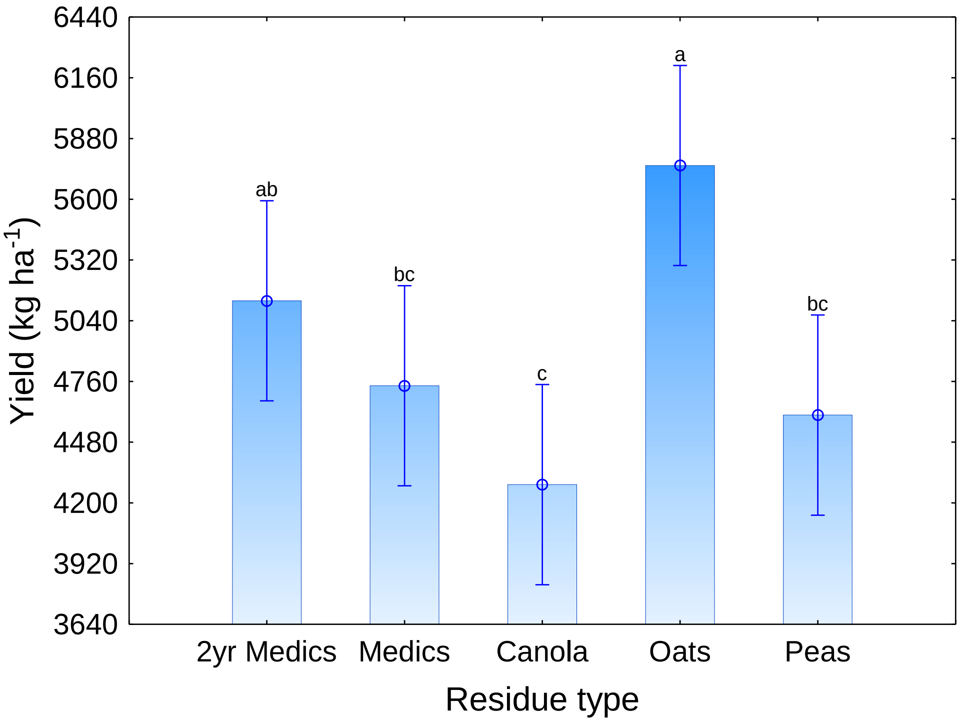

Figure 4.7: The grain yield of wheat in response to the residue type and the planter type in year two. Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

During year one, the protein content of the wheat grain was influenced ($p < 0.05$) by an interaction between the residue type and the planter type (Table 4.3). When planting into two-year and one-year medic residue the double disc planter led to the highest protein content while the single disc led to a slightly higher protein content in the canola, oat and lupin residue (Figure 4.8).

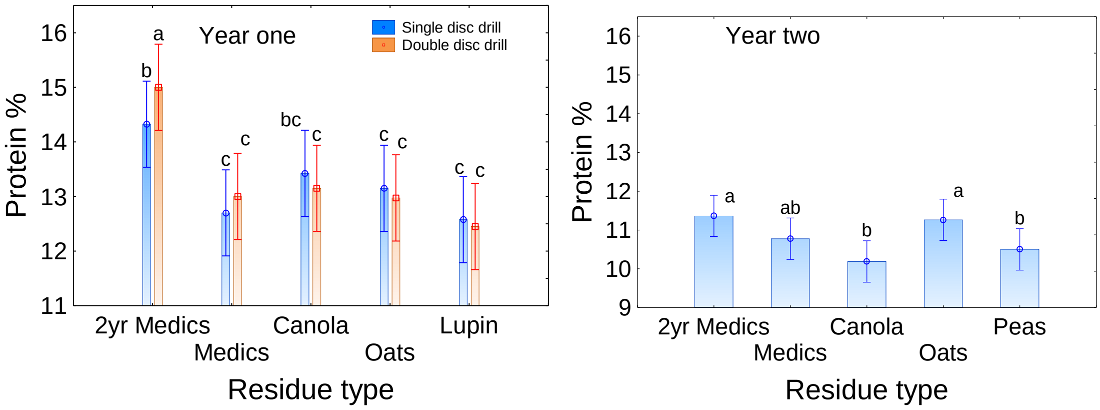

Figure 4.8: In year one and year two, the type of planter and type of residue's effect on the protein content (%) of wheat grain. Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals

During year two, the protein content of the wheat grain was not influenced ($p > 0.05$) by the planter type but was influenced ($p < 0.05$) by the residue type (Table 4.3). There was no interaction amongst the variables ($p > 0.05$). The two-year medic residue led to the highest protein content ($p < 0.05$) but was not different to the one-year medic and the oats residue ($p > 0.05$) (Figure 4.8). The canola residue led to the lowest protein content ($p < 0.05$) but was not different to the one-year medic residue and the pea residue ($p > 0.05$).

During year one, the hectolitre mass of wheat grain was influenced ($p < 0.05$) by the residue type and the planter type, there was no interaction ($p > 0.05$) between the variables (Table 4.3). The two-year medic residue led to the lowest HLM ($p < 0.05$) but was not different from the HLM obtained in the lupin residue ($p > 0.05$) (Figure 4.9). The canola and oat residue led to the highest HLM ($p < 0.05$) but was not different from the medic residue ($p > 0.05$). The single disc drill planter led to a higher HLM when compared to the double disc drill ($p < 0.05$) (Figure 4.9).

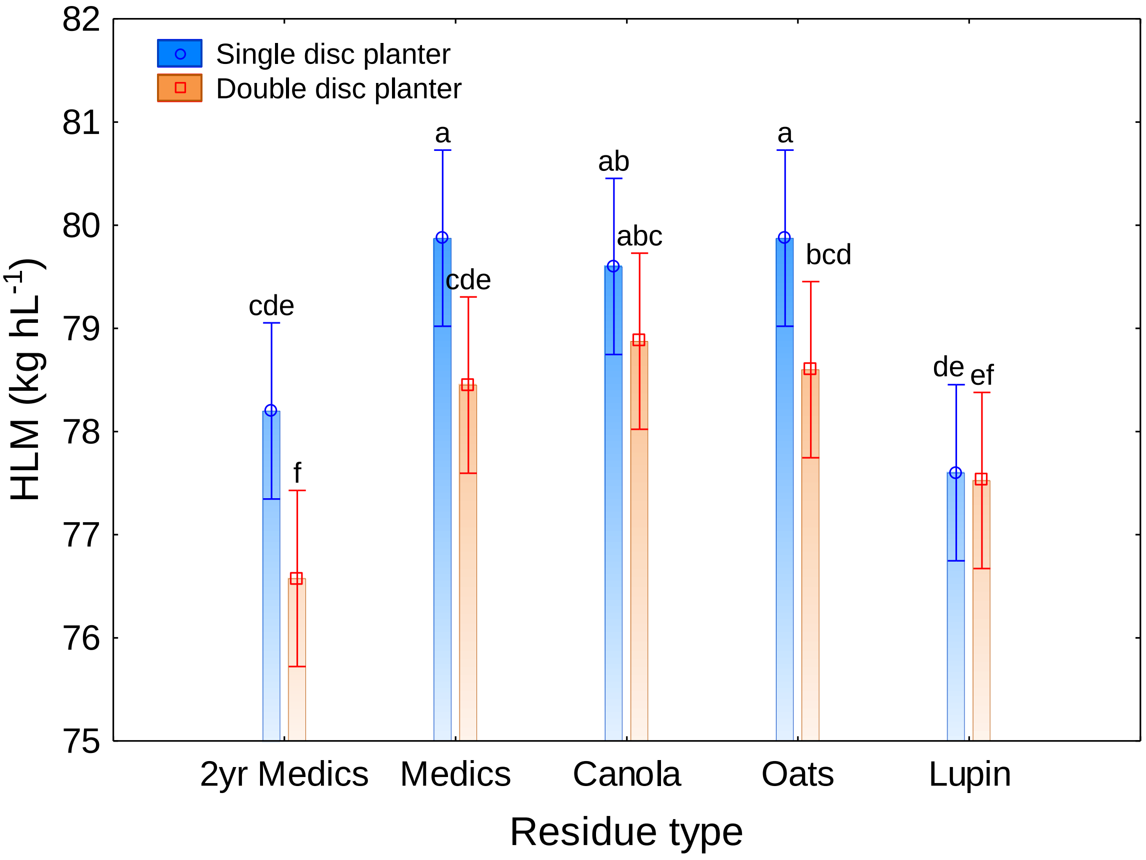

Figure 4.9: In year one, the hectolitre mass of the wheat grain in response to donor crop residue type and planter type. Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

During year two, the hectolitre mass of wheat grain was not influenced ($p > 0.05$) by either the planter type or the crop residue type (Table 4.3). There was no interaction amongst the variables ($p > 0.05$). The mean HLM of wheat was 75.25 kg hL^{-1} (results not shown).

During year one, the thousand kernel mass of wheat was not influenced ($p > 0.05$) by the residue type, planter type or their interaction (Table 4.3). The mean TKM of wheat was 33.99 g (results not shown).

During year two, the thousand kernel mass of wheat was not influenced ($p > 0.05$) by the planter type but was influenced ($p < 0.05$) by the crop residue type (Table 4.3). There was no interaction amongst the variables ($p > 0.05$). Oats and medic residues produced significantly (p < 0.05) higher TKM than two- year medics and peas residues (Figure 4.10).

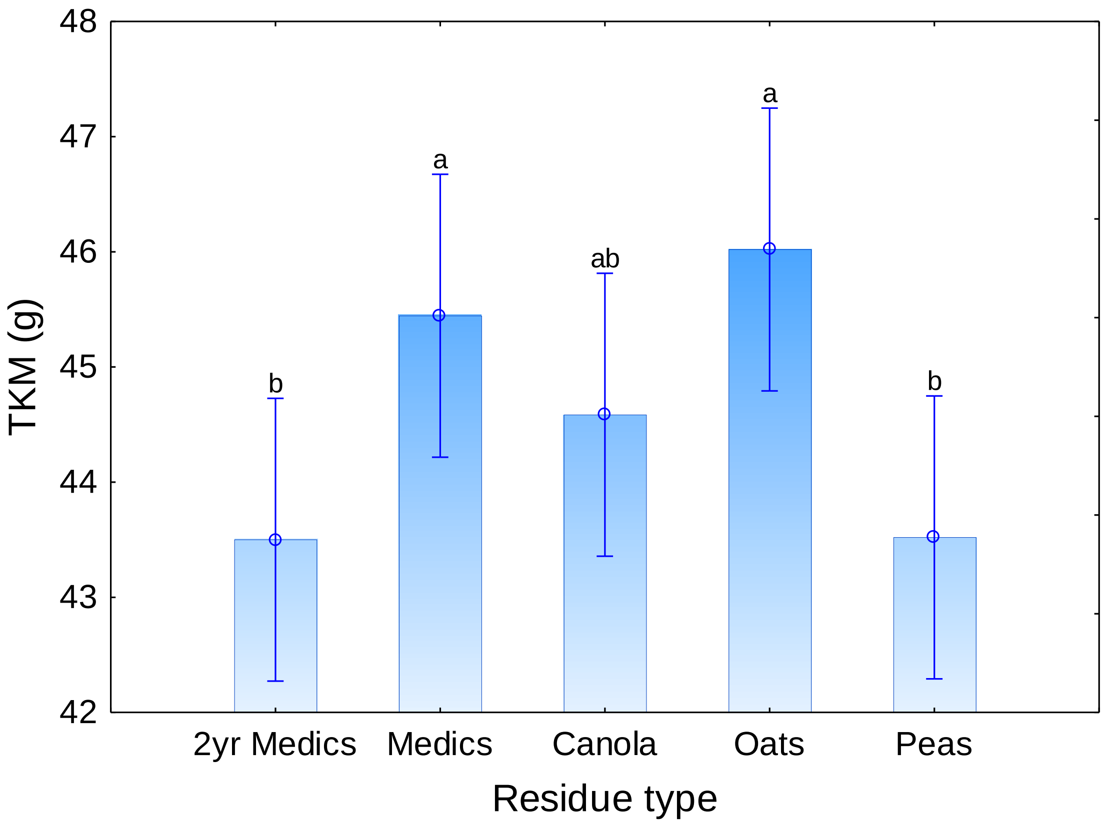

Figure 4.10: The thousand kernel mass of wheat in response to the crop residue type in year two. Letters on plots indicate which treatments were different (*p* < 0.05) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

4.3.5 Soil mineral nitrogen

During year one, the total mineral nitrogen content in the soil was not influenced (*p* > 0.05) by the planter type but was however influenced (*p* < 0.05) by the residue type and the sampling date (Table 4.4). There was no interaction between any of the variables (*p* > 0.05). At the first sampling date (30 DAE) the oat residue resulted in the lowest mineral N (*p* < 0.05). The two-year medic residue led to the highest mineral N (*p* < 0.05), but did not differ from the one-year medic residue or the lupin residue (*p* > 0.05) (Figure 4.11). At the second sampling (physiological maturity) the mineral N in the soil declined from the first sampling date (*p* < 0.05). There were no differences among the crop residue types mineral N at physiological maturity ($p > 0.05$) (Figure 4.11).

Table 4.4: ANOVA F statistics and *p* values for the model of total mineral nitrogen content for both years in response to crop residue type, planter type and date of sampling. Bold is used to illustrate *p* values < 0.05

Variable	**Total Mineral N**	
2019	F statistic	*p* value
Residue	5.92	**0.007**
Planter	0.36	0.592
Date	61.12	**0.004**
Residue*Date	3.21	0.052
Planter*Date	0.43	0.558
Residue*Planter	1.53	0.224
Residue*Planter*Date	0.57	0.684
2020		
Residue	4.66	**0.002**
Planter	0.30	0.585
Date	5.87	**0.018**
Residue*Date	0.77	0.547
Planter*Date	1.37	0.247
Residue*Planter	0.44	0.781
Residue*Planter*Date	0.17	0.954

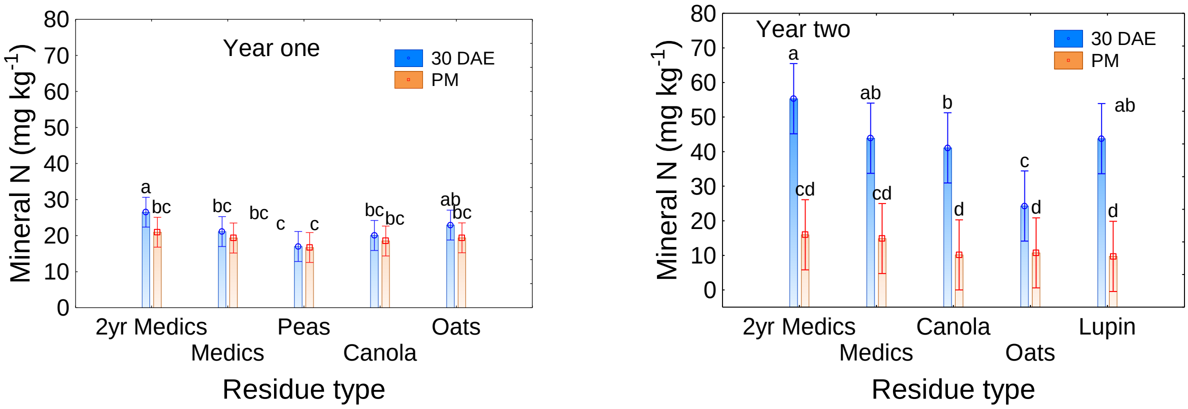

Figure 4.11: In year one and year two, the mineral nitrogen content in wheat plots at 30 DAE and physiological maturity (PM) in response to the crop residue type. No common letters on the bars indicate statistical difference at 5% level. Letters plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

During year two, the total mineral N in the soil was not influenced ($p > 0.05$) by the planter type but was influenced ($p < 0.05$) by the crop residue type and the date of sampling (Table 4.4). There was no interaction amongst the variables ($p > 0.05$). At the first sampling date the pea residue resulted in the lowest mineral N ($p < 0.05$) (Figure 4.11). The one-year medic residue and the canola residue did not result in total N different to that of the pea residue ($p > 0.05$). The two-year medic residue resulted in the highest mineral N ($p < 0.05$) but was not different to the oat residue ($p > 0.05$). At the second sampling date the mineral N declined ($p < 0.05$) (Figure 4.11). The residue types did however not result in mineral N differences (p > 0.05).

Experiment 2: Barley

4.3.6 Donor crop residue load

During year one, the donor crop residue load was influenced (F = 10.18; $p < 0.05$) by the residue type. The canola residue resulted in the highest residue load ($p < 0.05$), but did not differ from the wheat residue load ($p > 0.05$) (Table 4.5). The one-year medics resulted in the lowest residue load ($p < 0.05$), but did not differ from the two-year medic residue load ($p > 0.05$).

Table 4.5: The crop residue load (kg ha^{-1}) present at the time of planting for both years. No common letters indicate significant difference at a 5% level

Residue type	**Residue load (kg ha^{-1})**
2019	
Two-year medic	1930^{b}
One-year medic	1590^{b}
Canola	3404^{a}
Wheat	3310^{a}
2020	
Two-year medic	1087^{b}
One-year medic	2117^{a}
Canola	2631^{a}
Wheat	2575^{a}

During year one, the crop residue load was very poorly correlated ($p < 0.05$; $r^2 = 0.157$) to the grain yield of barley. Higher residue loads led to a slight grain yield increase (results not shown).

During year two, the donor crop residue load was influenced (F = 5.13; $p < 0.05$) by the donor crop residue type. Canola residue led to the highest residue load ($p < 0.05$), but was however not different to the wheat and one-year medic residue ($p > 0.05$) (Table 4.5). The two-year medic residue resulted in the lowest residue load ($p < 0.05$).

During year two, the crop residue load was not correlated ($p > 0.05$; $r^2 = 0.123$) to the grain yield of barley (results not shown).

4.3.7 Plant population

In both years the plant population of barley was not influenced ($p > 0.05$) by the type of residue but was influenced ($p < 0.05$) by the planter type (Table 4.6). There was no interaction amongst the variables ($p > 0.05$). The double disc planter resulted in a better establishment compared to the single disc drill ($p < 0.05$). In year one the double disc planter led to a mean plant population of 79 plants m^{-2} and the single disc planter resulted in a mean plant population of 57 plants m^{-2} (results not shown). In year two the double disc planter led to a mean plant population of 89 plants m^{-2} and the single disc planter led to a mean plant population of 75 plants m^{-2} (results not shown).

4.3.7 Biomass

During year one, the biomass of barley at 30 DAE was not influenced ($p > 0.05$) by the residue type but was influenced ($p < 0.05$) the planter type (Table 4.6). There was no interaction amongst the variables ($p > 0.05$). The double disc planter led to a mean biomass of 108 kg ha^{-1} and the single disc drill resulted in a mean biomass of 70 kg ha^{-1} (results not shown).

During year two, the biomass of barley 30 DAE was not influenced ($p > 0.05$) by the residue type, the planter type, or their interaction (Table 4.6). There was however a tendency for the type of residue to influence the biomass ($p = 0.073$). Canola crop residue tended to lead to the highest barley biomass. The mean biomass of barley was 344 kg ha^{-1} (results not shown).

In both years, the biomass of barley 60 DAE was not influenced ($p > 0.05$) by the residue type, the planter type, or their interaction (Table 4.6). During year one, the mean biomass of barley was 789 kg ha^{-1} (results not shown). In year two, the mean biomass of barley was 5344 kg ha^{-1} (results not shown).

In both years, the biomass of barley 90 DAE was not influenced ($p > 0.05$) by the residue type, the planter type, or their interaction (Table 4.6). In year one, the mean biomass was 4184 kg ha^{-1} (results not shown). In year two, the mean biomass was 5878 kg ha^{-1} (results are not shown).

Table 4.6: ANOVA F statistics and *p*-values for the models of barley plant population, biomass at 30, 60 and 90 days after emergence (DAE), as well as biomass at physiological maturity, in response to planter type and crop residue type. Bold is used to illustrate *p* values < 0.05

		Plant population		**Biomass 30 DAE**		**Biomass 60 DAE**		**Biomass 90 DAE**		**Biomass maturity**	
	Variable	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value
2019											
	Residue type	2.16	0.163	2.34	0.141	2.10	0.170	1.80	0.218	1.10	0.397
	Planter type	18.67	**0.023**	13.29	**0.036**	2.88	0.188	2.43	0.217	0.12	0.748
	Interaction	0.99	0.440	0.46	0.791	1.33	0.323	0.77	0.542	1.52	0.274
2020											
	Residue type	0.55	0.656	2.69	0.073	1.33	0.292	2.11	0.130	2.09	0.132
	Planter type	18.36	**<0.001**	0.07	0.788	0.39	0.538	0.03	0.866	1.33	0.262
	Interaction	0.21	0.886	1.09	0.377	0.73	0.545	0.04	0.990	0.89	0.462

In both years the biomass of barley at physiological maturity was not influenced ($p > 0.05$) by the residue type, the planter type or their interaction (Table 4.6). During year one, the mean biomass was 4002 kg ha^{-1} (results not shown). In year two, the mean biomass of barley was 14914 kg ha^{-1} (results not shown).

3.3.8 Yield components, grain yield and quality parameters

During year one, the number of ear-bearing tillers of barley was not influenced ($p > 0.05$) by planter type but was influenced ($p < 0.05$) by the residue type (Table 4.7). There was no interaction between the variables ($p > 0.05$). The wheat residue led to the highest number of ear-bearing tillers and the two-year medic residue led to the lowest number ($p < 0.05$) (Figure 4.12).

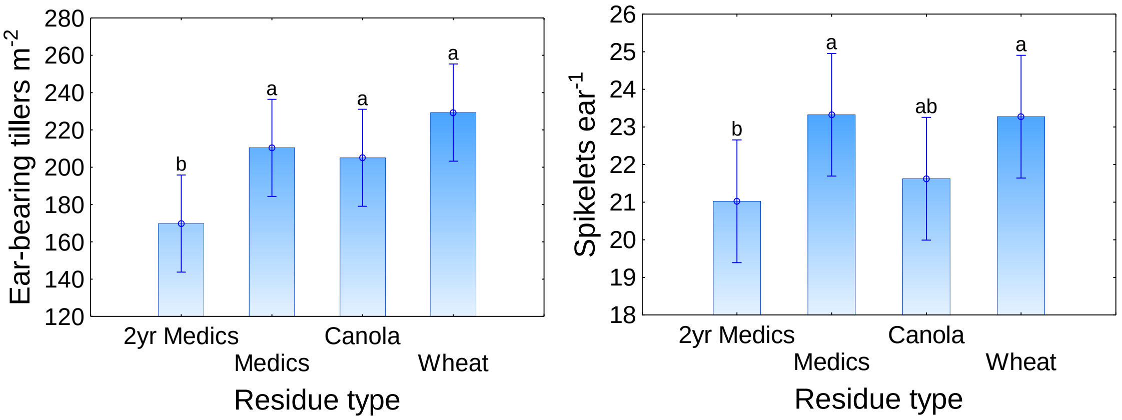

Figure 4.12: In year one, the number of ear-bearing tillers and the number of spikelets for barley in response to donor crop residue type. Letters plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

During year two, the number of barley ear-bearing tillers was not influenced ($p > 0.05$) by the donor crop residue type but was influenced ($p < 0.05$) by the planter type (Table 4.7). The double disc planter resulted in a mean of 367 ear bearing tillers m^{-2} and the single disc planter resulted in a mean of 300 ear bearing tillers m^{-2} ($p < 0.05$) (results not shown).

Table 4.7: ANOVA F statistics and *p*-values for the models of barley ear-bearing tillers, spikelets per ear, grain yield, protein content, hectolitre mass, thousand kernel mass and kernel plumpness in response to planter type and residue type. Bold is used to illustrate $p < 0.05$

	Ear-bearing tillers		**Spikelets**		**Grain yield**		**Protein content**		**Hectolitre mass**		**Thousand kernel mass**		**Kernel plumpness**	
Variable	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value
2019														
Residue type	5.32	**0.022**	4.39	**0.037**	5.29	**0.022**	20.96	**<0.001**	1.12	0.390	9.24	**0.004**	10.51	**0.003**
Planter type	6.54	0.083	3.19	0.172	12.64	**0.038**	2.26	0.230	0.01	0.946	0.01	0.918	5.03	0.111
Interaction	0.84	0.503	1.30	0.333	2.46	0.129	6.95	**0.010**	2.53	0.123	3.51	0.063	0.80	0.526
2020														
Residue type	2.56	0.082	0.98	0.421	7.91	**0.001**	9.11	**<0.001**	0.72	0.552	0.54	0.659	5.50	**0.006**
Planter type	9.96	**0.005**	3.19	0.089	2.29	0.145	0.88	0.358	0.21	0.650	0.53	0.476	1.07	0.313
Interaction	0.66	0.587	1.47	0.252	0.33	0.801	0.59	0.626	2.56	0.083	0.42	0.738	0.61	0.615

During year one, the spikelets per ear of barley was not influenced (*p* > 0.05) by the planter type but was influenced (*p* < 0.05) by the residue type (Table 4.7). There was no interaction between the variables (*p* > 0.05). One-year medic and wheat residues resulted in significantly (p < 0.05) higher spikelets per ear than two-year medic residue (Figure 4.12).

During year two, the number of spikelets per ear of barley was not influenced (*p* > 0.05) by the donor crop residue type, the planter type or their interaction (Table 4.7). The mean number of spikelets per ear was 23.90 (results not shown).

During year one, the grain yield of barley was influenced (*p* < 0.05) by the residue type and the planter type (Table 4.7). There was no interaction between the variables (*p* > 0.05). When planting into canola the highest yield was obtained (*p* < 0.05), but was however not different from the wheat and one-year medic residue treatments (*p* > 0.05) (Figure 4.13). The two-year medic residue led to the lowest yield (*p* < 0.05), but was however not different to the one-year medic residue (*p* > 0.05). The double disc drill led to higher grain yields (*p* < 0.05) (Figure 4.13).

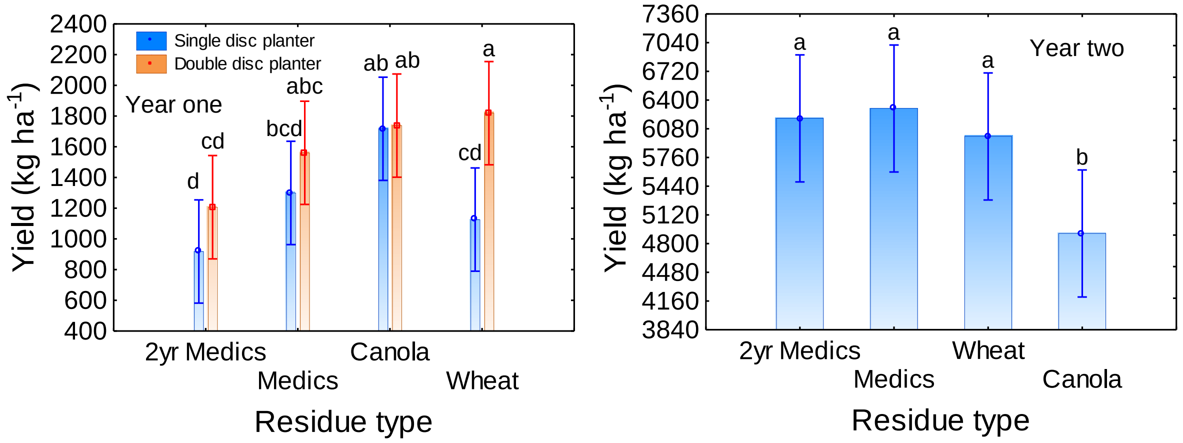

Figure 4.13: In year one and year two, the grain yield of barley in response to the residue type and the planter type. Letters on plots indicate which treatments were different (*p* < 0.05) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

During year two, the grain yield of barley was influenced (*p* < 0.05) by the crop residue type but was not influenced (*p* > 0.05) by the planter type (Table 4.7). There was no interaction amongst the variables (*p* > 0.05). The one-year medic residue resulted in the highest barley yield (*p* < 0.05), but was not different to the two-year medic residue and the wheat residue ($p > 0.05$) (Figure 4.13). The canola residue led to the lowest barley yield ($p < 0.05$).

During year one, the protein content (%) of barley grain was influenced ($p < 0.05$) by an interaction between the crop residue type and the planter used (Table 4.7). The planter type did not influence ($p > 0.05$) the protein content in all residue types except the wheat residue and the one-year medic residue. The single disc planter resulted in a higher protein content in the wheat and one-year medic residue compared to the double disc planter ($p < 0.05$) (Figure 4.14).

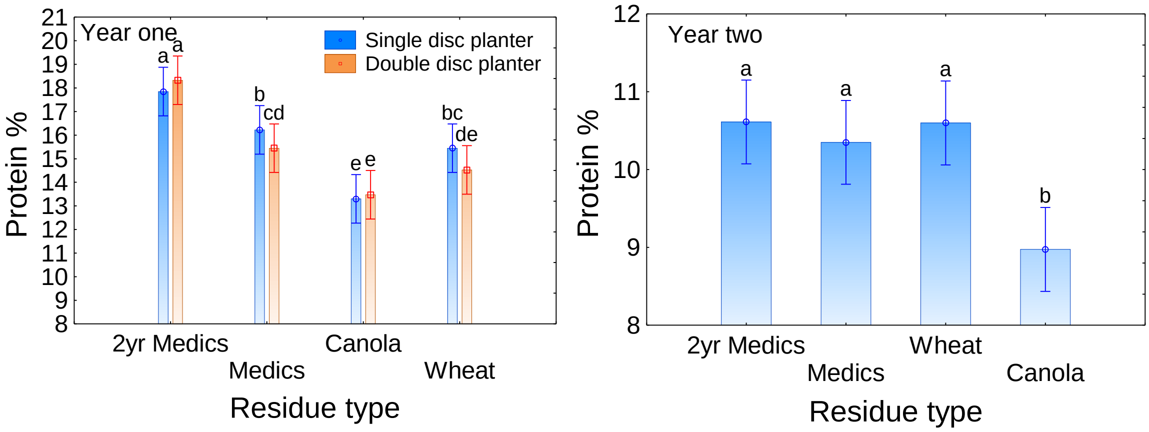

Figure 4.14: In year one and year two, the protein content of barley grain in response to the planter type and type of crop residue. Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

During year two, the protein content of barley grain was not influenced ($p > 0.05$) by the planter type used, but was influenced ($p < 0.05$) by the crop residue type (Table 4.7). The two-year medic residue resulted in the highest protein content ($p < 0.05$) but was however not different to the one-year medic residue and the wheat residue ($p > 0.05$) (Figure 4.14). The canola residue led to the lowest protein content in barley grain ($p < 0.05$).

In both years, the hectolitre mass of barley grain was not influenced ($p > 0.05$) by the crop residue type or the planter type, there was no interaction amongst the variables (Table 4.7). The HLM in year one was 68.11 kg hL^{-1} (results not shown). The HLM in year two was 66.34 kg hL^{-1} (results not shown).

During year one, the thousand kernel mass of barley was influenced ($p < 0.05$) by the crop residue type but was not influenced ($p > 0.05$) by the planter type (Table 4.7). There was no interaction amongst the variables ($p > 0.05$). The wheat residue resulted in the highest TKM ($p < 0.05$), but was however not different to the canola and one-year medic residue (Figure 4.15). The two-year medic residue resulted in the lowest TKM for barley ($p < 0.05$).

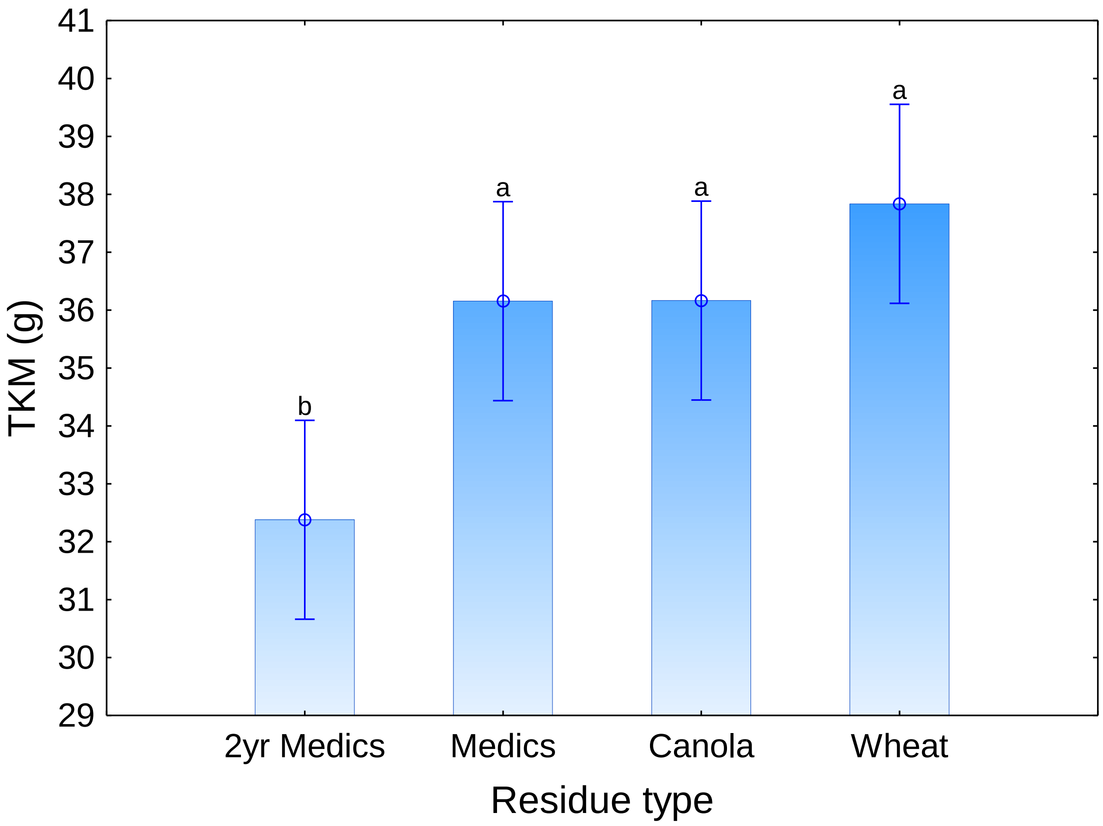

Figure 4.15: In year one, the thousand kernel mass (g) of barley grain in response to different crop residue types. Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

During year two, the thousand kernel mass of barley grain was not influenced ($p > 0.05$) by the crop residue type or the planter type, there was no interaction amongst the variables (Table 4.7). The mean TKM (g) of barley grain was 47.36 (results not shown).

During year one the percentage plump kernels of barley was not influenced ($p > 0.05$) by the planter type but was however influenced ($p < 0.05$) by the crop residue type

(Table 4.7). There was no interaction amongst the variables. Wheat crop residue resulted in the highest % plump kernels ($p < 0.05$), but was however not different to the one-year medic and canola residue ($p > 0.05$) (Figure 4.16). The two-year medic residue resulted in the lowest % plump kernels ($p < 0.05$).

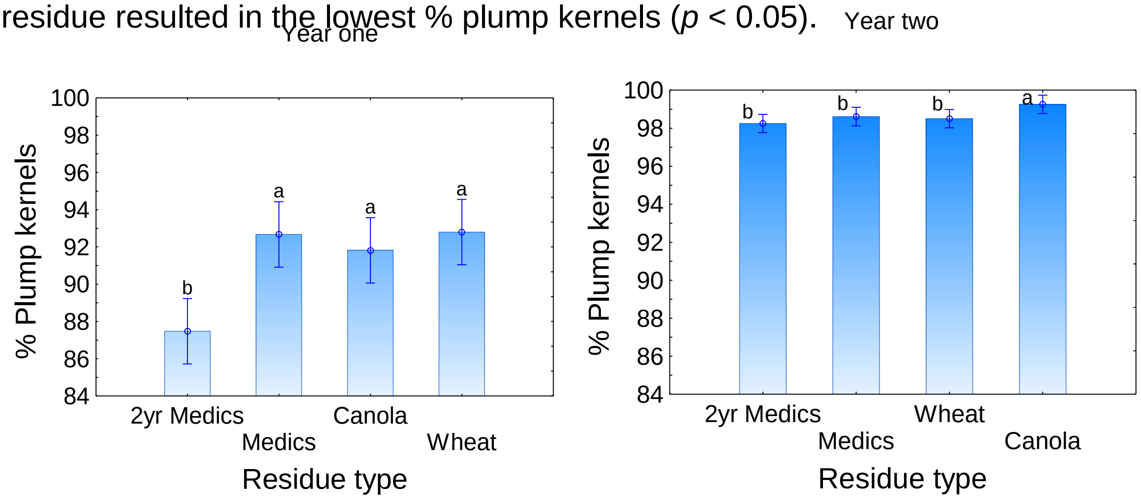

Figure 4.16: The percentage plump kernels of barley in year one and year two in response to the crop residue type. Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

During year two, the percentage plump kernels of barley was not influenced ($p > 0.05$) by the planter type but was influenced ($p < 0.05$) by the crop residue type (Table 4.7). There was no interaction amongst the variables ($p > 0.05$). The canola crop residue led to the highest % plump kernels ($p < 0.05$) (Figure 4.16). The two-year medic residue led to the lowest % plump kernels ($p < 0.05$), but was not different to the wheat and the one-year medic residue ($p > 0.05$).

4.3.9 Soil mineral nitrogen

During year one, the total mineral nitrogen in the soil was not influenced ($p > 0.05$) by the type of planter but was however influenced ($p < 0.05$) by the residue type and the sampling date (Table 4.8). There was no interaction amongst the variables ($p > 0.05$). At the first sampling date 30 days after emergence the two-year medic residue resulted in the highest mineral N content ($p < 0.05$), the mineral N content in the soil was however not different to the one-year medic residue ($p > 0.05$) (Figure 4.17). The wheat residue led to the lowest mineral N content in the soil ($p < 0.05$), but was however not different to the canola residue ($p > 0.05$). At the end of the season at physiological maturity, there was still some mineral N present in the soil profile but was lower than the 30 days after emergence sampling ($p < 0.05$) (Figure 4.17). This led to a high nitrogen % in the kernels, thus making it unsuitable for malting barley and leading the grain to be dropped to feed quality. The two-year medic residue led to the highest mineral N content at the end of the season ($p < 0.05$), but was however not different to the wheat residue ($p > 0.05$). The canola residue resulted in the lowest mineral N content in the soil at the end of the season ($p < 0.05$), but was not different to the one-year medic and wheat residue ($p > 0.05$).

Table 4.8: ANOVA F statistics and *p* values for the model of total mineral nitrogen content for both years in response to crop residue type, planter type and date of sampling. Bold is used to illustrate *p* values < 0.05

Variable	**Total mineral N**	
2019	F statistic	*p* value
Residue	7.68	**0.007**
Planter	0.28	0.632
Date	117.92	**0.001**
Residue*Planter	0.08	0.971
Residue*Date	0.39	0.761
Planter*Date	0.63	0.484
Residue*Planter*Date	0.16	0.923
2020		
Residue	1.95	0.134
Planter	0.26	0.610
Date	4.38	**0.042**
Residue*Planter	0.10	0.961
Residue*Date	1.80	0.159
Planter*Date	0.00	0.998
Residue*Planter*Date	0.17	0.915

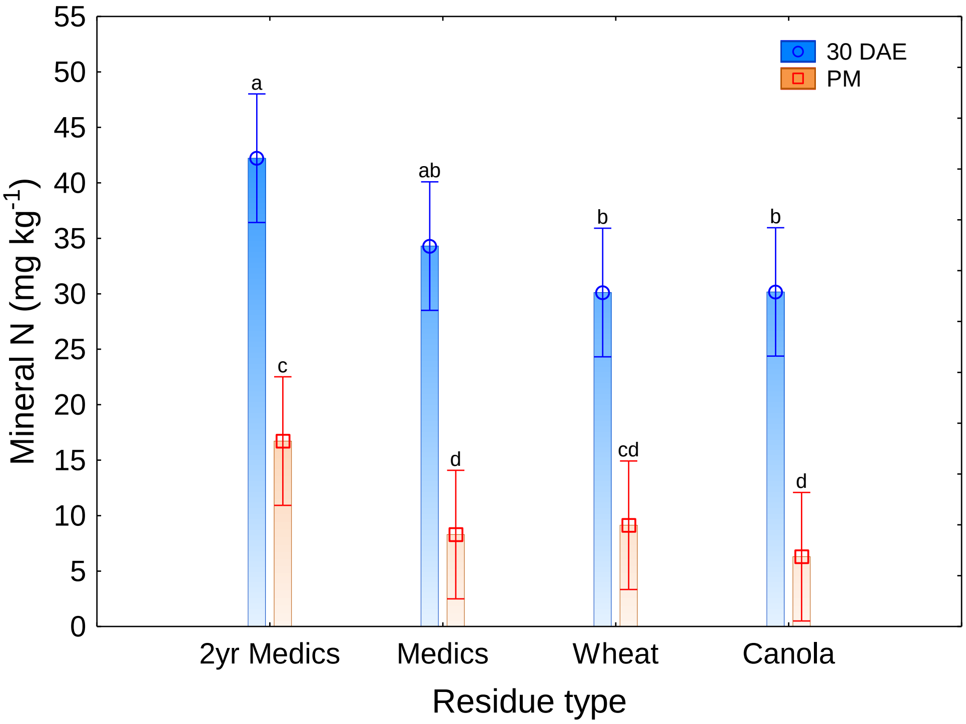

Figure 4.17: In year one, the mineral nitrogen content in barley plots at 30 DAE and physiological maturity (PM) in response to the crop residue type. No common letters on the bars indicate statistical difference at 5% level. Vertical bars denote 95 % confidence intervals.

During year two, the total mineral nitrogen was not influenced ($p > 0.05$) by the crop residue type and the planter type but was influenced ($p < 0.05$) by the date of sampling (Table 4.8). There were no interactions amongst the variables ($p > 0.05$). The total N in the soil was higher at 30 DAE (22.2 mg kg^{-1}) than at physiological maturity (19.6 mg kg^{-1}; results are not shown).

Experiment 3: Canola

4.3.10 Donor crop residue load

During year one, the donor crop residue load was influenced (F = 18.46; $p < 0.05$) by the residue type. The barley residue resulted in the highest residue load ($p < 0.05$), but did not differ from the wheat residue load ($p > 0.05$) (Table 4.9). The one-year medic resulted in the lowest residue load ($p < 0.05$), but did not differ from the two-year medic residue load ($p > 0.05$). Year one the donor crop residue load was not correlated ($p > 0.05$; $r^2 = 0.005$) to the canola grain yield (results not shown).

Table 4.9: The crop residue load (kg ha^{-1}) present at the time of planting for both years. No common letters indicate significant difference at a 5% level

Residue type	**Residue load (kg ha^{-1})**
2019	
Two-year medic	2265^{b}
One-year medic	1607^{b}
Barley	4873^{a}
Wheat	4667^{a}
2020	
Two-year medic	2600^{a}
One-year medic	1803^{b}
Barley	2759^{a}
Wheat	2487^{a}

In year two the donor crop residue load was influenced (F = 6.37; $p < 0.05$) by the type of crop residue. The barley residue resulted in the highest residue load but was not different ($p > 0.05$) to the two-year medic residue or the wheat residue (Table 4.9). The one-year medic residue resulted in the lowest crop residue load ($p > 0.05$). During year two the crop residue load was not correlated ($p > 0.05$; $r^2 = 0.002$) to the canola grain yield (results not shown).

4.3.11 Plant population

During year one, the plant population of canola was influenced ($p < 0.05$) by an interaction between the residue type and the planter type (Table 4.10). The single disc planter generally led to a higher plant population in all residue except for the two-year medic residue (Figure 4.18).

Table 4.10: ANOVA F statistics and *p*-values for the models of canola plant population, biomass at 30, 60 and 90 days after emergence (DAE), as well as biomass at physiological maturity, in response to planter type and crop residue type. Bold is used to illustrate *p* values < 0.05

		Plant population		**Biomass 30 DAE**		**Biomass 60 DAE**		**Biomass 90 DAE**		**Physiological maturity**	
	Variable	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value
2019											
	Residue type	0.31	0.815	3.01	0.087	3.28	0.073	1.96	0.191	1.91	0.198
	Planter type	3.53	0.157	0.52	0.523	5.71	0.097	3.08	0.177	2.90	0.187
	Interaction	5.48	**0.020**	0.16	0.918	1.04	0.420	1.86	0.207	4.54	**0.034**
2020											
	Residue type	0.72	0.548	0.45	0.718	1.27	0.308	0.22	0.879	0.71	0.556
	Planter type	22.84	**<0.001**	5.44	**0.030**	1.45	0.242	3.44	0.078	1.35	0.258
	Interaction	0.87	0.472	0.37	0.775	1.04	0.397	0.60	0.619	0.34	0.795

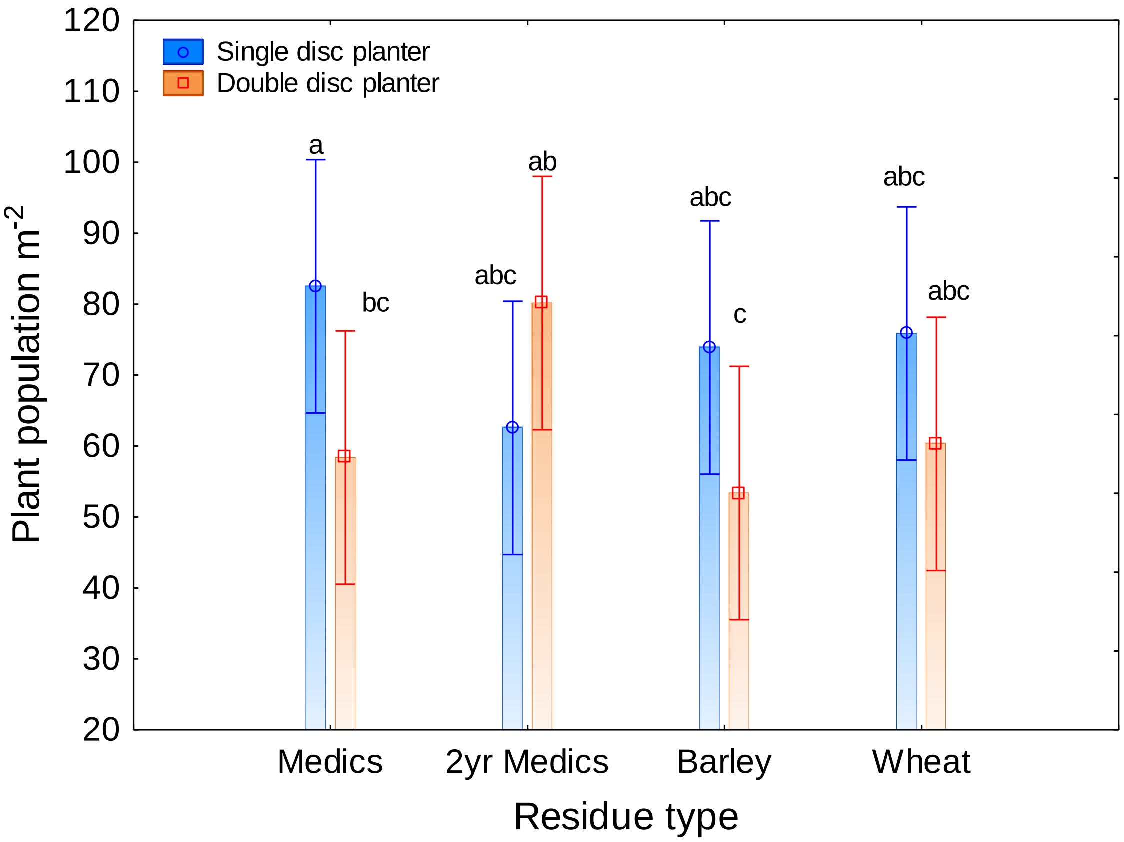

Figure 4.18: In year one, the effect of residue type and planter type on the plant population of canola. Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

During year two, the plant population of canola was not influenced ($p > 0.05$) by the residue type but was however influenced ($p < 0.05$) by the planter type (Table 4.10). There was no interaction amongst the variables ($p > 0.05$). The single disc planter led to a mean plant population of 56 plants m^{-2} and the double disc planter led to a mean plant population of 37 plants m^{-2} ($p < 0.05$) (results not shown).

4.3.12 Biomass production

During year one, the biomass of canola 30 DAE was not influenced ($p > 0.05$) by the residue type, the planter type or their interaction (Table 4.10). The mean biomass of canola 30 DAE was 155 kg ha^{-1} (results not shown).

During year two, the biomass of canola 30 DAE was not influenced ($p > 0.05$) by the residue type but was influenced ($p < 0.05$) by the planter type (Table 4.10). There was no interaction between the variables ($p > 0.05$). The double disc planter resulted in a canola biomass of 221 kg ha^{-1} and the single disc planter resulted in a mean biomass of 107 kg ha^{-1} ($p < 0.05$) (results not shown).

During year one, the biomass of canola 60 DAE was not influenced ($p > 0.05$) by the residue type, the planter type or their interaction (Table 4.10). The mean biomass of canola 60 DAE was 2219 kg ha^{-1} (results not shown).

During year two, the biomass of canola 60 DAE was not influenced ($p > 0.05$) by the residue type, the planter, or their interaction (Table 4.10). The mean biomass of canola 60 DAE was 9645 kg ha^{-1} (results not shown).

During year one, the biomass of canola 90 DAE was not influenced ($p > 0.05$) by the residue type, the planter type or their interaction (Table 4.10). The mean biomass of canola 90 DAE was 5343 kg ha^{-1} (results not shown).

During year two, the biomass of canola 90 DAE was not influenced ($p > 0.05$) by the residue type, the planter or their interaction (Table 4.10). The mean biomass was 4481 kg ha^{-1} (results not shown).

During year one, the biomass of canola at physiological maturity was influenced by an interaction ($p < 0.05$) between the residue type and the planter type (Table 4.10). The double disc planter resulted in a higher biomass in medic residue while the single disc planter resulted in a higher biomass in wheat and barley residue (Figure 4.19).

During year two, the biomass of canola at physiological maturity was not influenced ($p > 0.05$) by the donor crop residue type, planter type or their interaction (Table 4.10). The mean biomass of canola was 7941.41 kg ha^{-1} (results not shown).

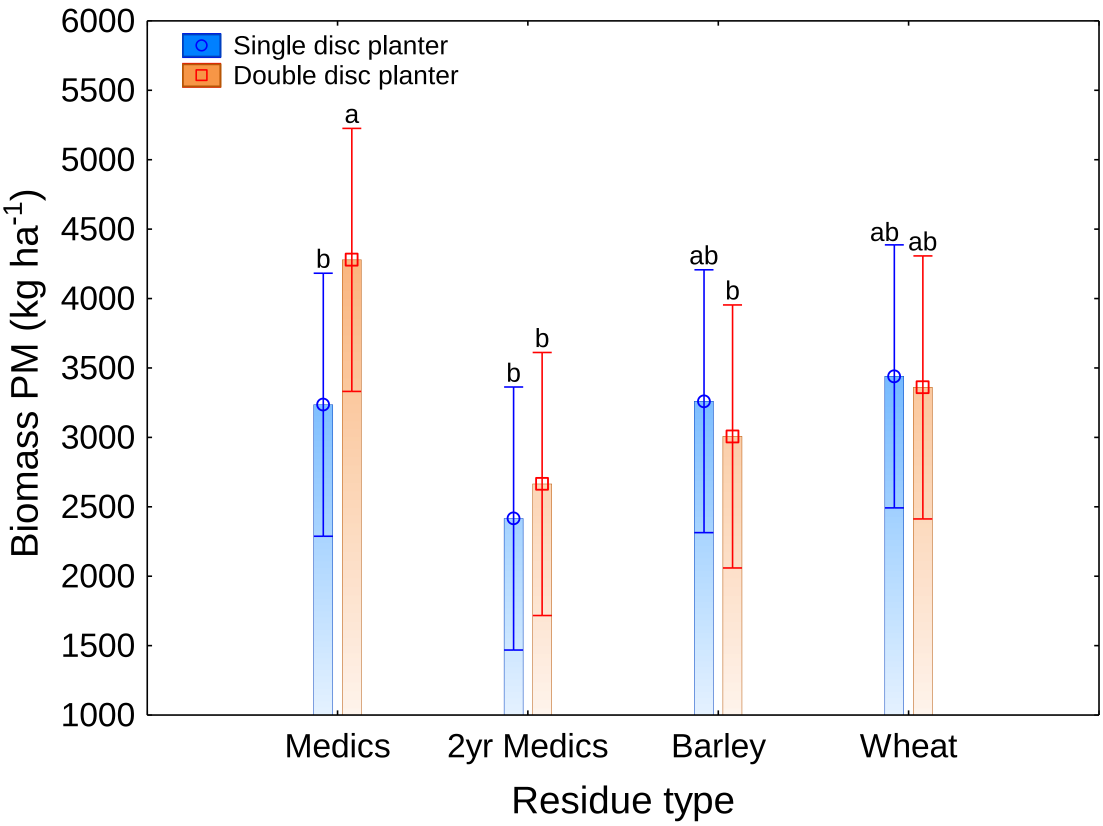

Figure 4.19: In year one, the biomass of canola at physiological maturity in response to the residue type and the planter type used. Letters on plots indicate which treatments were different (p < 0.05) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

4.3.13 Yield and quality parameters

During year one, the grain yield of canola was influenced (p < 0.05) by an interaction between the residue type and the planter type (Table 4.11). The double disc planter resulted in higher yields in one-year medic and barley residues while the single disc planter resulted in higher yields in two-year medic and wheat residues (Figure 4.20). These differences were generally not significant.

During year two, the grain yield of canola was not influenced (p > 0.05) by the crop residue type or the planter type (Table 4.11). There was no interaction amongst the variables (p > 0.05). The mean grain yield of canola was 3091 kg ha^{-1} (results not shown).

Table 4.11: ANOVA F statistics and *p* values for the models of canola grain yield, thousand kernel mass and oil content in response to planter type and residue type. Bold is used to illustrate *p* values < 0.05

		Grain yield		**Thousand kernel mass**		**Oil content**	
	Variable	F statistic	*p* value	F statistic	*p* value	F statistic	*p* value
2019							
	Residue type	1.58	0.262	3.42	0.066	13.96	**0.001**
	Planter type	0.05	0.846	1.49	0.310	2.60	0.205
	Interaction	4.40	**0.036**	0.70	0.577	2.23	0.154
2020							
	Residue type	1.46	0.254	0.49	0.698	9.82	**<0.001**
	Planter type	0.27	0.611	0.03	0.876	0.74	0.400
	Interaction	0.89	0.462	2.68	0.098	0.33	0.800

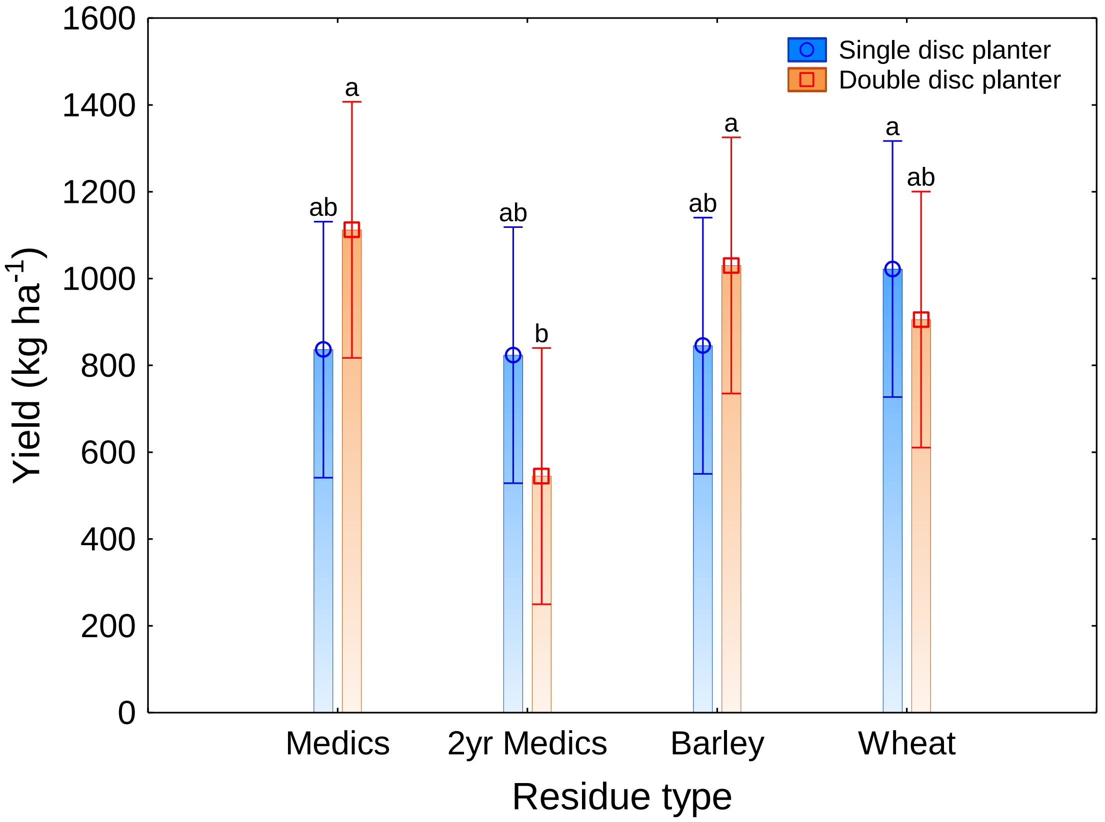

Figure 4.20: In year one, the grain yield of canola in response to the residue type and the planter type. Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

The thousand kernel mass of canola in both years was not influenced ($p > 0.05$) by the residue type, the planter type, or their interaction (Table 4.11). In year one, there was however a tendency ($p = 0.066$) for the wheat residue to lead to a higher thousand kernel mass. In year one the mean thousand kernel mass of canola was 2.83 g (results not shown). In year two the mean thousand kernel mass of canola was 3.67 g (results not shown).

During year one, the oil content of canola was not influenced ($p > 0.05$) by the planter type but was influenced ($p < 0.05$) by the residue type (Table 4.11). There was no interaction between the variables ($p > 0.05$). The wheat residue resulted in the highest oil content while the two-year medic residue resulted in the lowest oil content ($p < 0.05$) (Figure 4.21).

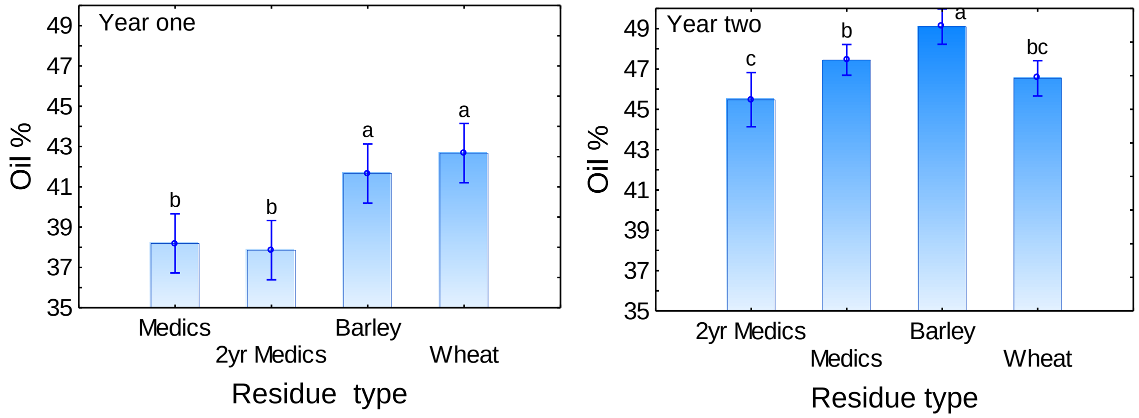

Figure 4.21: Year one and year two, the oil content (%) of canola in response to the type of donor crop residue. Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons. Vertical bars denote 95 % confidence intervals.

During year two, the oil content of canola was not influenced ($p > 0.05$) by the planter type but was influenced ($p < 0.05$) by the crop residue type (Table 4.11). There was no interaction amongst the variables ($p > 0.05$). The barley crop residue led to the highest oil content ($p < 0.05$) (Figure 4.21). The two-year medic residue led to the lowest oil content ($p < 0.05$) but did not differ from the wheat crop residue ($p > 0.05$).

4.3.14 Soil mineral nitrogen

During year one, the total mineral nitrogen content of the soil in the canola plots was influenced ($p < 0.05$) by an interaction between the donor crop residue type and the sampling date (Table 4.12). There were no other interactions between the variables ($p > 0.05$). The mineral nitrogen content in the soil decreased in all residue types from the first sampling date to the second ($p < 0.05$) (Figure 4.22). The medic residue resulted in higher mineral N content at the first sampling when compared to the barley and wheat residue ($p < 0.05$). There were no differences ($p > 0.05$) in mineral N content among residue types at the second sampling date.

During year two, the total mineral N content in the soil was not influenced ($p > 0.05$) by the crop residue type and the planter type but was influenced ($p < 0.05$) by the date of sampling (Table 4.12). There was no interaction amongst the variables ($p > 0.05$). The total N was higher 30 DAE (24.7 mg kg^{-1}) compared to physiological maturity (19.4 mg kg^{-1}) ($p < 0.05$; results not shown).

Table 4.12: ANOVA F statistics and *p* values for the model of mineral nitrogen content (mg kg^{-1}) of the soil in response to residue type, planter type and date of sampling. Bold is used to illustrate *p* values < 0.05

Variable	**Total mineral N**	
2019	F statistic	*p* value
Residue	6.54	**0.012**
Planter	0.88	0.417
Date	108.53	**0.002**
Residue*Planter	0.85	0.485
Residue*Date	5.14	**0.024**
Planter*Date	2.68	0.200
Residue*Planter*Date	2.47	0.095
2020		
Residue	1.00	0.399
Planter	1.54	0.220
Date	13.69	**0.001**
Residue*Planter	1.18	0.326
Residue*Date	1.20	0.319
Planter*Date	0.07	0.787
Residue*Planter*Date	0.59	0.627

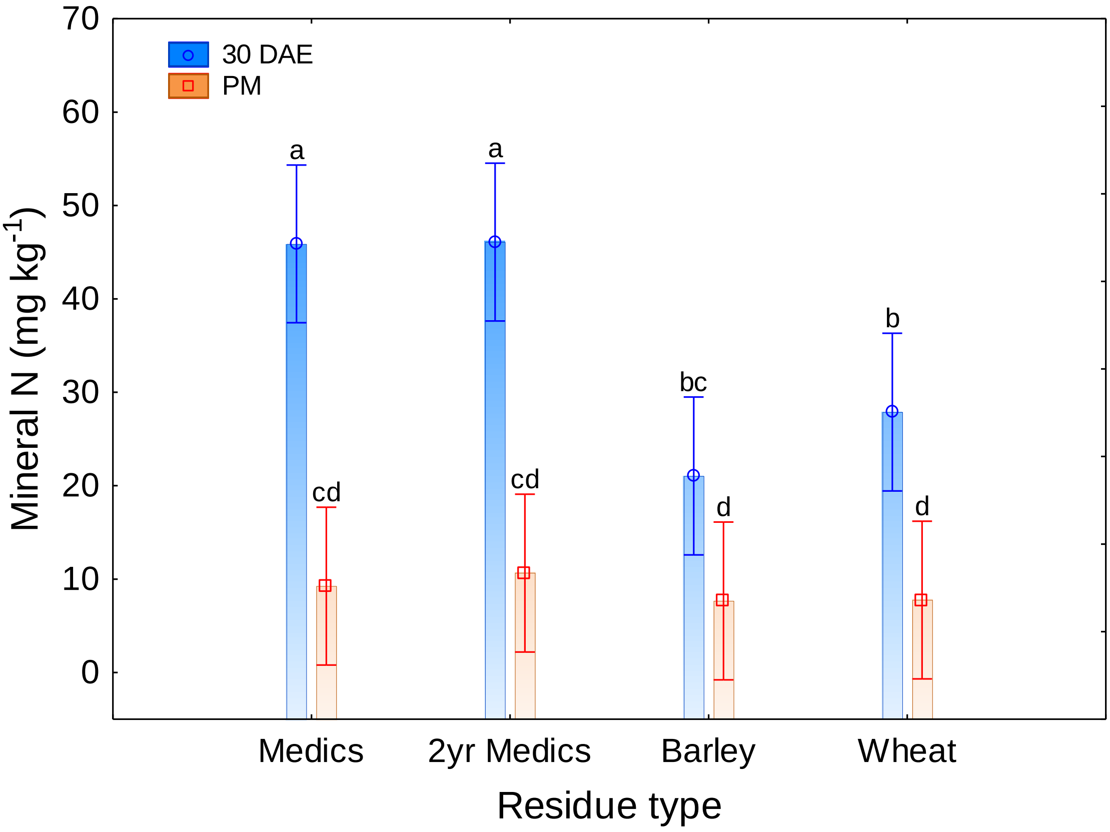

Figure 4.22: In year one, the mineral nitrogen content in canola plots soil at 30 days after emergence and at physiological maturity (PM). Letters on plots indicate which treatments were different ($p < 0.05$) from one another according to the post-hoc pairwise comparisons.

4.4 Discussion

The type of planter had a significant impact on the wheat, barley and canola production. Wheat and barley both had higher ($p < 0.05$) plant populations when established with the double disc planter. The double disc planter with the disc furrow openers being slightly offset, slightly moved the crop residue out of the furrow to the interrow space. When the seed furrow is cleaned, negative physical effects due to crop residue can be alleviated (Azooz and Arshad 1998). The double disc planter may have had more pressure on the closing wheels compared to the single disc planter due to the design of the unit. Poor seed to soil contact may lead to poor establishment and ultimately a potential yield penalty (Morris *et al.* 2010). Good seed to soil contact is especially critical when crop with small seed size such as canola is planted (Swanepoel *et al.* 2019; Swanepoel and Labuschagne 2020).

The drought conditions prior to and in the first year of the study led to relatively small donor crop residue loads (Table 4.1, 4.5 and 4.9). Negative effects due to physical effects may however be limited due to the small residue loads. Generally residue loads above 5000 kg ha^{-1} may have negative impacts on the following crop (Bruce *et al.* 2006). The canola had a higher plant population when established with the single disc planter. The single disc planter however had shallower seed depth placement which was evident from the worn edge on the discs during planting. The better depth placement of the single disc planter compared to the double disc planter favoured canola establishment. Large seeds contains more energy reserves (Harker *et al.* 2015). Placing canola seed deeper in the soil may have reduced the emergence (Malhi and Gill 2004). Due to the small seed size of canola and limited energy reserves depth placement in the soil is critical to a good establishment.

Soil processes, physical and allelopathic effects from crop residue cannot be separated from each other in the field as the results seen are a combination of these factors. The physical effects of crop residue on the subsequent crop are likely very limited in our study due to the relatively small crop residue loads. The possibility for allelopathic effects may also be limited. The crop residue had time to degrade over the summer months and became less toxic (Purvis 1990). Concern have been raised due to the fact that allelopathic studies are often done in the absence of a soil medium (Morris *et al.* 2010). In the presence of soil, allelopathic effects may be limited due to microbial breakdown and adsorption of allelochemicals (Wu *et al.* 2001).

The type of planter used had an influence or at least a tendency on production of biomass of the crops 30 days after emergence (Figure 4.5). This may be ascribed to higher plant populations for wheat and barley when the double disc planter was used, and the single disc planter led to higher canola plant populations. In year one, as the season progressed the crops were able to compensate for lower plant population however, in the second year when large differences among plant populations were recorded, the wheat crop was unable to compensate in biomass (Table 4.2). It appears as if canola is able to better compensate in biomass for low plant populations compared to wheat and barley (Table 4.10). Canola forms more flowering branches while wheat and barley form more tillers when competition amongst plants are low (Swanepoel *et al.* 2019).

In year one the donor crop residue type seemed to play a bigger role on the mineral N content in the soil compared to year two (Figure 4.11). The mineral N content in the soil was higher in the first year compared to the second year. In year two there was no difference in mineral N content of the soil among residue types (Table 4.8 and 4.12). This may be attributed to the drought conditions, in severe drought medics fix less N (Graham and Vance 2000). The higher soil mineral N in certain residue types may have led to larger crop biomass. Due to the low crop residue loads that has limited physical effects on the subsequent crop the soil processes likely had the biggest influence on the subsequent crop. Year one biomass of wheat at 60 and 90 days after emergence was influenced by the residue type and not the planter type in year one (Figure 4.5). The large difference in soil mineral nitrogen content from year one to year two may partly be affected by the different types of soil analyses used as explained in the material and methods.

The number of ear-bearing tillers of wheat in year one had a tendency and in year two, was more in the double disc planter treatments. This may be attributed to the higher plant population found in the double disc treatments. The number of ear-bearing tillers of barley in year one was influenced by the type of donor crop residue (Figure 4.12) and in year two by the planter type used. In year two, the higher plant population of the double disc planter may have resulted in the increased number of ear-bearing tillers. In year one, the two-year medic residue led to the lowest number of ears per square meter while wheat led to the highest number of ears. This may be attributed to the high mineral N found in the two-year medic residue plots. Legume species such as medics, lupins and peas fix nitrogen and can fix between 30–160 kg of N per hectare per year (Peoples and Baldock 2001). The amount of N fixed by legume species is dependent on sufficient nodulation (Graham 1981). This may explain why the pea residue did not result in high levels of mineral N. Due to the severe drought in year one, the amount of N was excessive in medics residue while the wheat residue had a higher residue load and conserved more moisture. Increased soil moisture later in the season will likely offset the negative effects of a moderate to high residue load on the early growth (Bruce *et al.* 2006).

The number of spikelets per ear of wheat and barley is determined early in the season, while the plants are is still the vegetative growth stage (Wang and Engel 1998). The number of barley spikelets per ear was influenced by the residue type in year one (Figure 4.12). Yield components are increased when nutrients is sufficient during the vegetative stages of crops (Abedi *et al.* 2011). The spikelets per ear was not influenced in year two in both wheat and barley. This may be attributed to the similar soil nitrogen content amongst the residue types. One could argue that if the first year was not a drought year the residue type would have had a larger influence on the following crop.

The planter type had an influence on the grain yield of barley in year one which may be attributed to the higher plant population when seeded with the double disc planter. The residue types with the highest mineral N present resulted in the lowest yields while the residue types which produces more biomass resulted in higher yields. As mentioned, the N may have been excessive in the drought year. The crop residue types which has a higher biomass may have conserved more moisture throughout the growing season. The canola grain yield in year one was influenced by an interaction between the crop residue types and the planter type. The residue type all led to similar yields while the double disc planter and single disc planter led to better yield in the different crop residue combinations. The planter type used was not correlated to the crop residue load. The fluctuations between the planter types may be attributed to some plots having a higher stones content on the soil surface leading to inconsistent crop establishment. During year two the crop residue types that resulted in the highest mineral N content in the soil led to the highest grain yields in barley and wheat (Figure 4.7 and 4.13).

The grain quality parameters such as the protein content in wheat and barley was influenced by the crop residue type (Figure 4.8 and 4.14). The protein content of seed has a positive linear relationship to the amount of nitrogen present which is similar to other studies done (Abedi *et al.* 2011). Parameters such as the hectolitre mass of wheat and barley is mostly dependent on climatic factors (Nel *et al.* 1998). The hectolitre mass of wheat was however influenced by the crop residue type in year one. Crop residue types which led to a higher soil mineral N content reduced the hectolitre mass (Figure 4.9).

4.5 Conclusion

The type of planter influenced the plant population of the different crops ($p < 0.05$), but due to the ability of crops to compensate when competition amongst them is low and the conditions is favourable the type of planter used did not affect the grain yield in year two. Where the difference amongst the plant populations was great and the climatic factors unfavourable, the plants were unable to compensate and a yield difference could be seen. In year one, the yield was influenced by the planter type or tended to be influenced. The double disc drill led to better wheat and barley yields.

The type of residue had an influence on the production of crops ($p < 0.05$). The residue types with a higher residue load led to higher yields in barley in year one. The cereal residue types led to the highest residue loads and did not lead to high soil mineral N contents in the first year. The high residue loads likely conserved more moisture compared to low residue loads. The residue types such as the legumes like medics produced less biomass and led to a higher mineral N content in the soil, due to year one's drought the amount of nitrogen was excessive. In the second year of the study when the climatic conditions were favourable, the residue types which resulted in a higher mineral N content in the soil resulted in the best yields. Wheat and barley are however more sensitive to the type of crop residue present compared to canola. Canola residue led to poor yields in the wheat and barley in the second year of the study, this might be because canola uses a lot of nitrogen and during the decomposition does not result in high levels of soil mineral N. It appears that a cereal crop planted after canola might need more nitrogen fertiliser. Wheat generally performed well on the medic and oats residue while barley performed well on the medics and wheat residue.

In this study, due to the small crop residue loads the physical effects of crop residue on the following crop could have been limited. It appears that how the soil processes were affected by crop residue likely had the biggest effect on the following crop. Nitrogen fertiliser programmes can be altered to account for any potential deficiencies caused by crop residues. The following crop planted after the second year of this study might however encounter physical effects from the crop residue. The crop residue loads will be high and proper seed placement may be difficult as well as overshading from the crop residue might be detrimental for emerging seedlings.

4.6 References

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Chapter 5: Decomposition of different types of crop residue in response to soil faunal decomposer communities

5.1 Introduction

Nutrient cycling is mediated by soil biota as a whole and is a key soil process for maintenance of crop production (Balestrini *et al.* 2015). Soil biota refers to microorganisms (fungi, bacteria and archaea) as well as soil fauna which all play a part in the decomposition process (Balestrini *et al.* 2015). Soil fauna can be described as organisms inhabiting the soil and litter strata (Petersen and Luxton 1982). The soil fauna can be further divided into micro-, meso-, and macro-fauna classes (Bradford *et al.* 2002). Micro fauna represents protozoa groups, meso fauna represents nematodes and microarthropods while macro fauna represents macro arthropods, earthworms, ants and termites (Coleman and Wall 2015). Soil fauna accelerates residue decomposition via fragmentation (Tian *et al.* 1992). Residue decomposition underpins the nutrient cycling processes (Carlesso *et al.* 2019). Decomposition dominated by fungal communities contributes more organic matter to stabile pools compared to bacteria (Horwarth 2015).

The speed of residue decomposition is determined by the quality characteristics of residue (such as the C:N ratio), environmental conditions and the amount of soil biota present (Nicolardot *et al.* 2001). The higher the C:N ratio, the slower the speed of decomposition (Nicolardot *et al.* 2001). Warm and moist conditions lead to a higher rate of decomposition (Guixiang *et al.* 2016). Soil biota tends to be more abundant in no-till managed soil compared to conventionally tilled soil (Reeleder *et al.* 2006). Thus, moving to Conservation Agriculture may lead to better nutrient cycling by managing the system to accommodate more soil biota. The application of certain groups of fungicides however, may have a detrimental effect on non-target soil fungi (Yang *et al.* 2011).

Understanding the process of crop decomposition and factors influencing the rate of decomposition will enable us to adapt management strategies to promote the cycling of nutrients and, in turn, improve the sustainability of cropping. The degradation of soils is associated with imbalanced, inadequate and pro-macronutrient fertiliser use together with the inadequate use of crop residue (Gupta *et al.* 2018). The degradation of the soil structure leads to slower decomposition, thus slower release of crop essential nutrients

(Carlesso *et al.* 2019). Improving nutrient cycling may reduce the need for inorganic fertilizers and may improve the soil structure. Residue with a low C:N ratio may lead to more stable organic carbon assimilation (Zhou *et al.* 2019). The addition of residue with a high C:N ratio may however provide a longer lasting source of nutrients for plants and may prevent leaching of nutrients (Truong *et al.* 2019).

It is hypothesised that (1) the residue with high C:N ratios will decompose slower compared to residue with a lower C:N ratio and (2) that the exclusion of soil meso- and macrofauna will lead to slower decomposition. The aim of the trial was to evaluate the decomposition rate of annual medics (*Medicago polymorpha*), oats (*Avena sativa*), lupine (*Lupinus angustifolius*), wheat (*Triticum aestivum*), barley (*Hordeum vulgare*) and canola (*Brassica napus*). The influence of micro-, meso- and macro fauna on decomposition was also evaluated.

5.2 Material and methods

5.2.1 Experimental design

The trial was conducted during 2019 at the Western Cape Department of Agriculture Tygerhoek research farm (34°09’58.3” S 19°54’34.1” E) near Riviersonderend in the Western Cape of South Africa. The area has a Mediterranean type climate with an average annual rainfall of 443 mm. The 2019 total rainfall was below average at 379 mm, however only 117 mm of rain was received within the growing season which made it an extremely dry cropping season. The average temperature was 14.8 °C and the average relative humidity 78.9 % for the duration the litterbags were in the field. The decomposition trail was conducted inside a long-term rotation trial. The decomposition trial has a varying number of replicates due to the fact that the long-term rotation trial had different donor crop residue and different test crop combinations (Table 5.1). Donor crop residue is derived from the previous year’s crop which was harvested, the test crop represents the crop that is seeded into the donor crop residue.

Table 5.1: Test crop and donor crop residue combinations leading to a varying number of replicates

Donor crop residue type	**Test crop**	**Total replications**
Two-year annual medics	Wheat, barley and canola	24
One-year annual medics	Wheat, barley and canola	24
Wheat	Barley and canola	16
Barley	Canola	8
Canola	Wheat and barley	16
Oats	Wheat	8
Lupin	Wheat	8

The trial was laid out as a randomised block design and had the following treatment factors: two types of litter bags, four litter bag removal dates, and the following residue types; barley, wheat, canola, lupin, oats, one-year medic and two-year medic. Overall, 832 litter bags were used in the trial. The residue was dried at 60 °C for 72 hours then placed into litter bags with different mesh sizes. The small mesh size litter bags had the following dimensions: 10 x 20 cm and a porosity of 50 microns ± 10 micron due to handling of the bags. The small mesh size litter bags permitted the entry of some of the micro fauna but mostly only bacteria and fungi (Carlesso, et al., 2019). The bigger mesh size litter bags had the following dimensions: 10 x 20 cm and a porosity of 2000 microns which allowed full access to soil biota (Carlesso, et al., 2019). All the litter bags were made of nylon plastic material that is not bio-degradable to ensure that the litter bags specifications will not change over time. Each bag was filled with five grams of crop residue and was permanently sealed. The canola residue was extremely brittle after the drying process and fell through the bigger mesh size litter bags, thus due to practical reasons some of the courser canola material was used to fill the mesh bags. The rest of the bags was filled was a representative sample of course and fine material trying to replicate in-field conditions. The bags were put in the field directly after planting on the 10th of May 2019.

5.2.2 Measurements

The removal of the litter bags took place at 30, 60, 90 and 150 days after planting with the 150 days after planting being prior to harvest of the bigger rotation trials. The litter bag removal process consisted of the litter bags being collected and dried at 60 ºC for 72 hours. The small mesh litter bags were weighed complete with bag and residue and the weight of the bag was subtracted. The weight of the big size mesh bags varied a lot, therefore each individual litter bag was cut open and the residue was extracted from the bag and weighed.

5.2.3 Statistical analyses

Linear mixed models were used to investigate the effect of residue type, removal date and mesh size on the rate of crop residue decomposition. The mass of the remaining residue after decomposition was winsorised to obtain normally distributed data. The fixed effects were residue type (one year of annual medics, two years of annual medics, barley, canola, oats, wheat and lupin), removal date (30, 60, 90 and 150 days after planting) and the mesh size (big and small) and all the combinations of interactions amongst them. The random effects were replications, the interaction between replication and residue type, the interaction between replication and removal date, the interaction between replication and mesh size, the interaction between replication, residue type and removal date and lastly the interaction between the replication, mesh size and removal date.

All data analyses were undertaken in Statistica version 13.5.0.17 (TIBCO 2019). Models were calculated in the package Mixed model ANOVA in R(Imer) package using Kenward-Rogers, with P-values for the significance of each variable were calculated using type III analyses of variance (ANOVA).

Post-hoc pairwise comparisons were calculated using the Probabilities for Post Hoc Tests package which computes contrasts between the least-squares means (LSD) of each level of factor. Pairwise comparisons were only conducted between levels of factors that were found to be significant ($p < 0.05$) in the ANOVA.

Results are displayed in line graphs. The vertical bars indicate the 95 % confidence intervals. Letters on plots indicate which treatments were different from one another according to the post-hoc pairwise comparisons.

5.3 Results

The decomposition of crop residue was influenced ($p < 0.05$) by the interaction between the residue type and the mesh size of the litterbags (Table 5.2). Some of the residue types such as the medic and lupin residue were more dependent on the decomposition mediated by meso and macro fauna compared to residue types with higher C:N ratios such as the wheat (Figure 5.1). All the residue types however decomposed faster in the presence of all soil biota (Figures 5.1 and 5.2). The crop residue decomposition was also dependant ($p < 0.05$) on the interaction between the removal date and the mesh size of the litter bags (Table 5.2). At later removal dates the residue was more decomposed compared to early in the season ($p < 0.05$). The decomposition slowed between the 60 and 90 days after planting measurements as the amount of residue left in the litter bags did not differ ($p > 0.05$). This decrease in the rate of decomposition might be due to lower temperatures experienced during that time in the winter.

Table 5.2: ANOVA F statistics and *p* values for the model of residue decomposition in response the type of residue, the removal date and the mesh size of the litter bags. Bold is used to illustrate *p* values <0.05

Variable	**F statistic**	***p* value**
Residue type	8.99	**<0.001**
Removal date	39.12	**<0.001**
Mesh size	275.43	**<0.001**
Residue type x Removal date	1.09	0.360
Residue type x Mesh size	5.03	**<0.001**
Removal date x Mesh size	6.08	**<0.001**
Residue type x Removal date x Mesh size	1.17	0.281

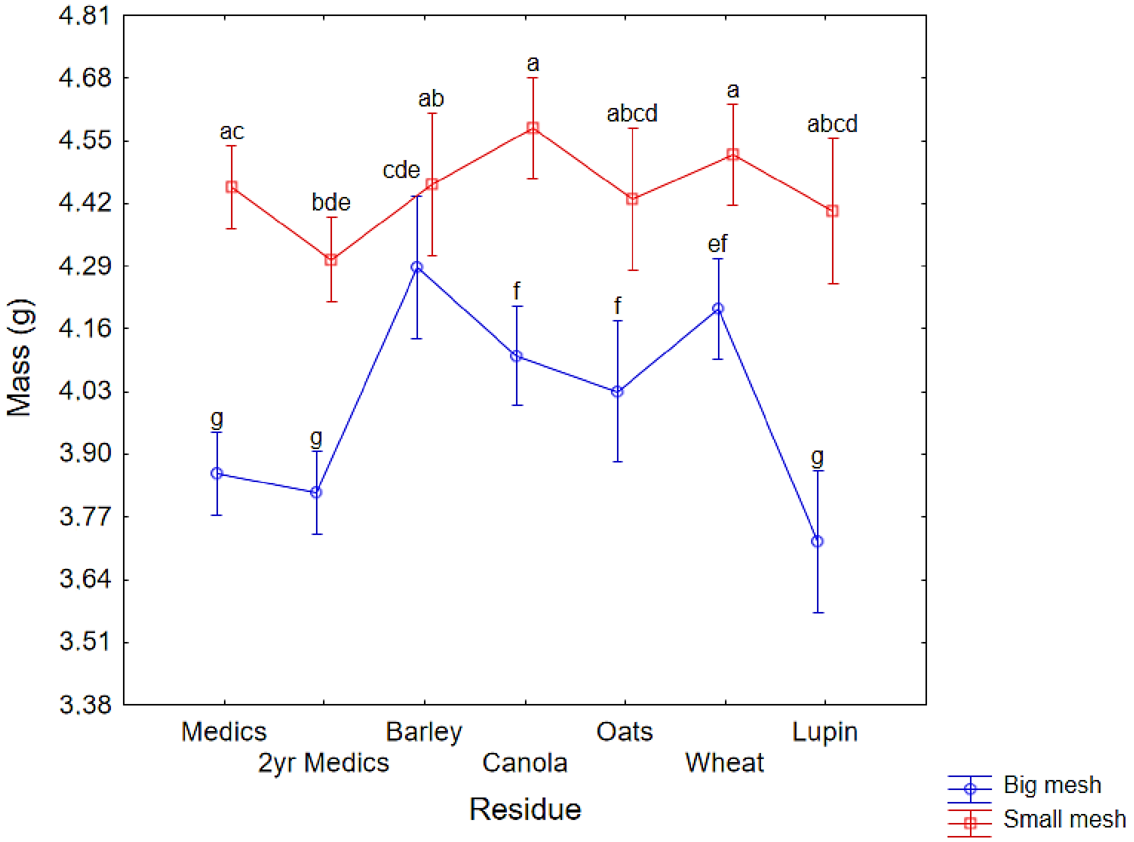

Figure 5.1: Decomposition of different types of crop residue in response to mesh bags with different size. On the Y-axis is the amount of residue left in the litter bag after the initial five grams of residue. On the X-axis is the type of residue which was used in the litter bag. The big mesh size was 2000 microns, and the small mesh size was 50 microns. No common letters on the bars indicate statistical difference at a 5 % level. Vertical bars denote 95 % confidence intervals.

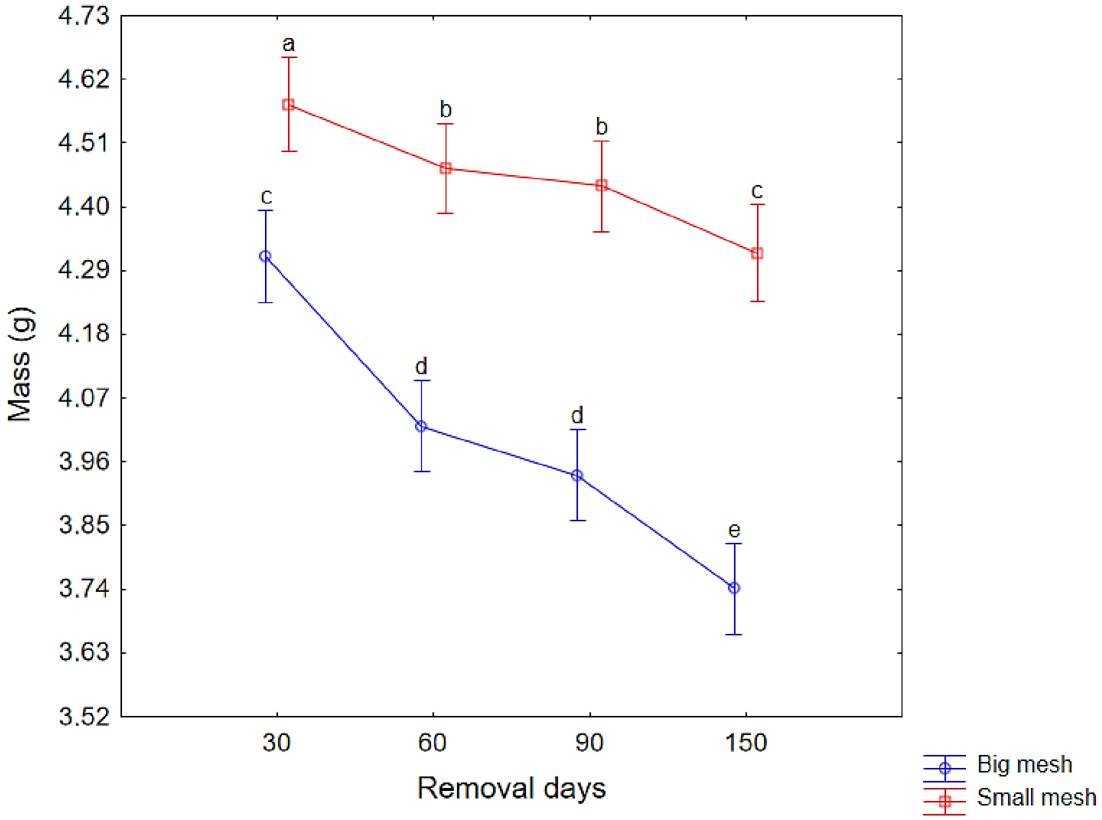

Figure 5.2: The decomposition of crop residue in response to the number of days the residue was in the field and to the mesh size of the litterbags. On the Y-axis is the amount of residue left in the litter bag after the initial five grams of residue. On the X-axis is the number of days the litter bags were in the field. The big mesh was 2000 microns, and the small mesh was 50 microns. No common letters on the bars indicate statistical difference at a 5 % level. Vertical bars denote 95 % confidence intervals.

5.4 Discussion

The type of donor crop residue and the different decomposer communities influenced the rate of decomposition (Figure 5.1). The type of crop residue is directly correlated to the different quality characteristics such as the C:N ratio (Huang *et al.* 2004). Residue with C:N ratios lower than 20 decomposes rapidly under favourable conditions (Huang *et al.* 2004). The approximate C:N ratios of the residue used in the study ranged from high to low: Wheat > Oats > Barley > Canola > Lupin > Medic residue (Huang *et al.* 2004; Murungu *et al.* 2011; Jensen 1997; Begum *et al.* 2014; Elgharably and Marschner 2011; Lefroy *et al.* 1995). The C:N ratio of wheat is approximately 64 and the C:N ratio of medic residue was approximately 13.5 (Huang *et al.* 2004; Lefroy *et al.* 1995). The C:N ratio of the crops may differ slightly from one season to the next depending on the climatic conditions and production practises. The residue with the lowest C:N ratios decomposed a lot faster than the residue such as wheat, barley and oats with higher C:N ratios, the pattern was however amplified in the big mesh litter size treatments where the full spectrum of soil biota was present (Figure 5.1). Residue with a low C:N ratio leads to more soil organic carbon sequestration compared to residue with a high C:N ratio (Zhou *et al.* 2019). Crop diversity may also improve the residue quality which may lead to the increase in organic carbon sequestration (Zhou *et al.* 2019). Including crops with a lower C:N ratio or increasing crop diversity in the rotation system may lead to higher levels of carbon assimilation. When the meso and macro fauna were excluded by means of the small mesh size litter bags, the decomposition among the different crop residue species was rather similar, but in the presence of an entire soil biotic community the type of residue had a more pronounced effect on the decomposition.

The residue decomposition rate differed more between the different mesh size litterbags later in the season when compared to early in the season (Figure 5.2). The interaction between removal date and different mesh size litter bags was significant ($p < 0.05$). These findings were similar to that of Carlesso et al. (2019) and Bradford et al. (2002) who found that the early stages of residue decomposition were more dependent on microbial processes. Mesh size effects such as residue loss due to handling may have occurred with the large mesh size litter bags. The loss due to handling may explain the fact that the decomposition differed significantly at the 30-day removal date (Figure 5.2). In the later stages the decomposition mediated by all groups of soil biota was more rapid, however none of the treatment combinations was completely decomposed. The amount of residue left in the litter bags did not change significantly between the 60 and 90 days after planting removal dates (Figure 5.2). This may be due to the cold temperatures experienced during that period. When cold periods are experienced during winter months and decomposition slows, the crop’s need may however be higher than the amount of nutrients released by nutrient cycling. It is important that nutrients are abundant during the critical growth period of the crops to obtain the yield potential (Dreccer *et al.* 2000). The critical period of wheat is the pre flower stages where the number of kernels are determined (Velasco *et al.* 2012). During the critical growth stages where the crop’s demand may exceed the amount of nutrients cycled through decomposition the application of inorganic fertilizer may improve crop yield.

Soil fauna is significantly higher in no-till managed soil compared to conventionally managed soils (House and Parmelee 1985). Soil fauna is known to fragment crop residue leading to faster decomposition (Tian *et al.* 1992). Soil fauna amplifies existing patterns of nutrients release including nitrogen mineralisation (Anderson *et al.* 1983). Thus, adopting management strategies to increase the amount of soil biota in the soil may lead to faster decomposition and in turn nutrient cycling. Being able to effectively cycle nutrients may lead to less inorganic fertilizer use and in turn may promote soil health (Gupta *et al.* 2018).

5.5 Conclusion

Nutrient cycling is underpinned by crop residue decomposition. The type of crop residue had an influence on the speed decomposition. The residue types with a higher C:N ratio decomposed slower compared to residue with a low C:N ratio. During the coldest winter month, the decomposition was the slowest but as the temperature increased the rate of decomposition increased. The early stages of decomposition are dominated by microbial decomposition however later in the season the decomposition mediated by all groups of soil biota was faster. Soil fauna is known to fragment crop residue and in turn amplifies existing patterns of nutrient release.

Adopting CA management strategies may increase the nutrient cycling in soils and in turn reduce our dependence on inorganic fertilizer. However, because of the high demand for nutrients during the critical period of crop growth and cold periods during the winter the use of inorganic fertilizer may alleviate any nutrient shortages.

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Chapter 6: General conclusion and future research

6.1 Conclusion

Adopting Conservation Agriculture (CA) practices may improve environmental, agronomic and economic sustainability in relatively dry Mediterranean climates (Calzarano *et al.* 2018). Local perception in the southern Cape is that in recent times producers tend to move more towards continuous cash cropping systems or at least to longer cropping sequences between pastures. The adoption of CA does not come without its challenges. For example, reduced yields may be observed when planting into large crop residue loads (dos Santos *et al.* 1993). Previous studies conducted over various parts of the world and in different climates generally ascribe poor growth in the presence of crop residue to allelopathy, physical effects and chemical effects such as nitrogen mineralisation or immobilisation. Some studies exclude some of the mechanisms such as allelopathy (Wynne *et al.* 2019), while other ascribe the effects mainly to allelopathy (Alsaadawi 2001). Field trials will likely represent a combination of abovementioned mechanisms, while laboratory trials will likely overestimate the potential of allelopathic effects. In the field allelopathic chemicals may be adsorbed to soil particles or decomposed by microbes (Wu *et al.* 2001).

The first objective of this research project was to evaluate the effect of crop residue extracts on the germination and germination parameters of wheat, barley and canola. The crop residue extracts were allelopathic in the absence of soil even after the residue had time to degrade over the summer months. The crop residue extracts of wheat, barley, canola, medics, oats and pea residue affected the germination percentage of barley and canola but did not affect the germination of wheat. Some residue types led to a reduction in germination percentage while other residue types slightly promoted germination (a mechanism called hormesis). The germination parameters such as coleoptile and radicle lengths, were generally affected more adversely compared to the germination percentages.

The second objective aimed to distinguish between physical and allelopathic effects of wheat residue on early growth of wheat, barley and canola under controlled conditions. In the presence of soil, allelopathic effects became less pronounced, to such an extent that it was negligible, at least for the southern Cape area where only a single crop is planted on a specific area per year and the residue had time to degrade. Degraded residue is less allelopathic compared to fresh residue (Purvis 1990). In the presence of large residue loads the subsequent crop may experience yield penalties (Bruce *et al.* 2006). Planters can struggle to accurately place seeds in high residue loads and ensure good seed-to-soil contact which may also lead to yield penalties (Morris *et al.* 2010). Although the trial was conducted in a glasshouse, conditions in the field with no-tillage planters were mimicked. Crop residue was placed on top of the soil in the pots, ensuring accurate seed placement and good seed to soil contact. The wheat and barley did not suffer penalties even at 8000 kg ha^{-1} residue loads. The canola however had stunted early growth at large residue loads in comparison to other crops. The response of canola might be attributed to its small seeds not having sufficient energy reserves to penetrate a thick residue load and still have energy left to invest in early leaf formation.

The third objective of the study was to evaluate the effect of different types of crop residue and two types of disc planters on crop production in the southern Cape of South Africa. The double disc planter cleaned the seed furrow more than the single disc planter. However, the single disc planter had better depth control. The double disc planter may reduce the physical effects of crop residue on the subsequent crop, but during our study the residue loads was not very high and as a result the physical effects may have been limited. The canola benefited from the better depth-control of the single disc planter which led to a higher plant population. The type of crop residue had an influence on the subsequent crop. Allelopathy likely played a negligible role in the field and physical effects was probably limited due to the low crop residue loads because of drought conditions. The effect that the crop residue has on the soil processes likely played the biggest role on the subsequent crop due to the climatic conditions when the study was conducted. In years where the crops yields are better, and the resulting crop residue load is higher, physical effects may play a bigger role on the subsequent crop.

The fourth objective of this study was to determine the rate of decomposition of different crop residue types and the influence that micro-, meso- and macro fauna communities had on crop decomposition. Crop residue from legume species decomposed faster than the cereal crop residue, due to their low C:N ratio. Crops with a high C:N ratio decompose slowly and may cause nitrogen immobilisation especially if incorporated. Residue decomposition is promoted by the soil fauna groups. Soil fauna is known to fragment crop residue leading to quicker decomposition and subsequently nutrient cycling (Tian *et al.*

1992). Enhancing the cycling of nutrients may lead to reduced dependence on inorganic fertilizers.

6.2 Limitations of the study

During the trial in the controlled glasshouse experiment, the soil used was unfortunately prone to surface crusting. This complicated the results since the no residue treatment, which was included to implicate no physical effects from residue on the subsequent crop, experienced surface crusting due to the impact from the water droplets. The seedlings struggled to break though the crust; this may have been comparable to physical effects of a residue load. The pots where residue was applied experienced less surface crusting thus the physical effects from crop residue alone could not be entirely isolated.

During the field trials, due to the drought conditions experienced in the field the residue loads was small which may have led to very limited physical effects from the crop residue on the subsequent crop. The residue loads in year one was rarely above 5000 kg ha^{-1} and in the second year of the study the residue loads was even smaller. Previous research done indicated that crop residue loads above 5000 kg ha^{-1} may lead to negative physical effects on the following crop (Bruce *et al.* 2006). The crop biomass was determined by sampling 10 plants per plot. Towards the end of the season, it became difficult to distinguish between the individual wheat or barley plants due to the number of tillers they had formed. The biomass determined is therefore likely an overestimation of the actual biomass present. To be able to make a better comparison between the planters, the planting depth should have been measured as well as the force applied by the closing wheels.

During the residue decomposition trial, the different residue types was not analysed for quality characteristics such as C:N ratio. The C:N ratio has a significant effect on the rate of residue decomposition and should be measured when a decomposition study is undertaken.

6.3 Future research

Relatively little research has been done examining the effect of crop residue on the subsequent crop, especially locally. Similar research is recommended to build up a data base on how certain crops react to different types of residue, taking the climate into account. Future research should aim to differentiate between the different effects of crop residue such as physical, biochemical or soil chemical processes being influenced by crop residue. Hopefully, the benefits of residue retention can be retained while focusing on ways to mitigate any yields loses or poor early growth in large residue loads.

The adoption of CA is rapid in South Africa, but producers are still sceptical about disc planters especially in very stony soil. Conversely, tine planters tend to get blocked easily in large residue loads. It is recommended that different types of planters are evaluated in depth in different crop residue loads and it's important to quantify the accurate placement of seeds in high residue loads. It would be interesting to see what effect row cleaners in front of the planting unit will have and if it would eliminate physical effects on crops and improve the placement of seed due to the absence of residue.

During the drought when the residue loads dropped from year one to year two the mineral N content in the soil also dropped. Following a drought year, it would have been better to apply more nitrogen fertiliser at topdressing. It would however be interesting to evaluate the mineral N content in the soil after a good cropping year. If nutrient cycling is sufficient the need for inorganic fertilisers may be very little. It remains relatively unclear how decomposer communities are impacted by herbicides, fungicides and nitrogen applications. Enough decomposers are needed to enable quick breakdown of the residue load before planting the next crop and is thus important to study the possible effect of synthetic inputs on decomposers should.

6.4 References

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