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Evaluation of cultivation, legume undersowing and nitrogen interventions on wheat development

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Evaluation of cultivation, legume undersowing and nitrogen interventions on wheat development

By

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for the Degree of Doctor of Philosophy*

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Declaration

I declare that this research is the result of my own work and except were stated and referenced otherwise, all the written work and investigations are my own. This work has not been accepted or submitted for an academic award elsewhere.

Karen E Rial Lovera

Dedication

To my beloved parents Juan and Rosa, who without their sacrifice, love and
encouragement I would not have achieved so much.

Anonymous.

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Abstract

Agriculture is facing increasing pressures to produce food that meets specific market and/or nutrition requirements, while using inputs in such a way that can ensure economic and environmental goals more efficiently. Two field experiments were conducted in 2013 and 2014 at the Royal Agricultural University's Harnhill' Manor Farm, Cirencester, UK to evaluate the influence of selected cultivation techniques, N fertilisation and undersowing legumes on spring wheat growth and development. To explore, in particular, the yield components contributing to grain yield and quality, as well as weed pressure influences together with changes in soil mineral N (SMN) content. Cultivation techniques included conventional tillage (CT), high intensity non-inversion tillage (HINiT) and low intensity non-inversion tillage (LINiT); mineral N fertilisation rates of 0, 70, 140 and 210 kg N ha^{-1} and two undersown legume species, black medic and white clover, plus no undersowing treatment. The performance of the management practices was strongly influenced by the weather. In 2013, under dry weather conditions, LINiT seems to be a suitable alternative to CT, while N fertilisation did not encourage greater grain yield. In 2014, CT appears to be a more reliable practice, while the application of up to 140 kg N ha^{-1} seemed to be enough to increase grain yield. Dry weather conditions at the time of broadcasting did not allow the undersowing species to be fully established, resulting in no effects on weed control and crop growth. In 2013, the initial poor plant establishment and slow crop growth under LINiT was compensated for by the soils ability to retain moisture, and thereby reducing crop water stress during the dry periods. This finally resulted in statistically similar grain yield to CT. In 2014 when water was not a limiting factor, poor plant establishment and crop growth, low SMN content and high weed pressure under LINiT resulted in lower grain yield than CT. In both years, HINiT resulted in low SMN content and high weed pressure resulting in poor grain yield. Across experiments, HINiT and LINiT saved energy-use and production costs, but CT could be more energy-use efficient and have high economic return if higher grain yield is assured. N fertilisation significantly promoted wheat growth, although under dry conditions with higher residual soil N, the N fertilisation did not increase yield. Under low SMN level applying up to 140 kg N ha^{-1} increased grain yield produced, but N fertilisation is energy consuming and its use does not always ensure a higher economic return.

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Abbreviations

ADAS	Agricultural Division of Advisory Service
ASAE	American Society of Agriculture Engineers
BM	black medic
ºC	degree Celsius (centigrade)
cm	centimetre
CT	Conventional tillage
DEFRA	Department for Environment, Food and Rural Affairs
DM	dry matter
FAO	Food and Agriculture Organization of the United Nations
g	grams
GS	growth stages
h	hour
ha	hectare
HGCA	Home-Grown Cereals Authority
HINiT	High intensity non-inversion tillage
IPCC	Intergovernmental Panel on Climate Change
kg	kilogram
kPa	kilo Pascal
l	litre
LINiT	Low intensity non-inversion tillage
LSD	Fisher's Protected Least Significant Difference
M	Molar
MAFF	Ministry of Agriculture, Fisheries and Food
mg	milligrams
min	minute
ml	millilitre

mm	millimetre
MPa	Mega Pascal
N	Nitrogen
N0	No nitrogen application
N70	70 kg N ha^{-1}
N140	140 kg N ha^{-1}
N210	210 kg N ha^{-1}
NABIM	National Association of British and Irish Millers
NIAB	National Institute of Agricultural Botany
NO$_3$-N	Nitrate nitrogen
NH$_4$-N	Ammonium nitrate
Nus	No undersowing
P	Phosphorus
ppm	parts per million
SED	Standard error of the difference
SMN	Soil mineral nitrogen
SOM	Soil organic matter
t	tonnes
TGW	Thousand grain weight
UK	United Kingdom
UKMO	United Kingdom Met Office
UN	United Nations
WC	white clover
§	section symbol

CHAPTER ONE

Introduction

1.1. Background

Since the nineteen seventies the global population has doubled and, according to projections of the United Nations Population Division, today's population (7.3 billions) is likely to reach over nine billions by 2050 and perhaps 10.9 billion by 2100 (United Nations, 2013, 2014). Most recent estimates by the Food and Agriculture Organization of the United Nations (FAO) and the Government Office for Science (GO-Science) suggest that feeding a world population of ten billion people will demand raising overall food production by 60% from 2005-2007 levels (FAO, 2013a; GO-Science, 2011). However, a growing population also means that more land is needed to build infrastructures; to produce bio-energy crops and biodiversity protection; further reducing the expansion for agriculture land (FAO, 2013a). To meet these demands, cereal production will have to grow (FAO, 2009; Hawkesford *et al.*, 2013; Semenov *et al.*, 2014) but cereal crop yield growth will probably be at slower rate than in the past, with a predicted slowdown to 0.7% per annum (4.3 tonne ha^{-1} by 2050) (FAO, 2009). Increased productivity is expected to be mainly from increases of yields and cropping intensity, and to a lesser extent from land expansion through sustainable intensification (Alexandratos & Bruinsma, 2012; Conway, 1998; Conway & Waage, 2010).

Global food production will also be challenged by unpredictable weather events, as result of changes to the climate due to the rise in greenhouse gases (GHGs) emissions, in some part from the effect of denitrification of nitrate fertilisers (Reynolds & Borlaug, 2006a,b; HGCA, 2012; Jenkinson, 2010). In fact, projections suggest that by 2030 the release of N_2O, as a GHG, will increase by 35 to 60% due to increases in N fertilisation and manure production (FAO, 2003). In order to avoid major climate changes, global emission of GHGs must reportedly be reduced by at least 50-60% (IPPC, 2007). Smith *et al.* (2007) suggested that by 2030 the potential mitigation options in agriculture will be about 89% from soil carbon sequestration, 9% from mitigation of methane and 2% from mitigation of soil N_2O emissions. The considerable challenge for plant and crop scientists' for the next century is to increase crop yields while reducing the use of

fertilisers and fossil fuel (Hamilton, 2009), and increasing resources-use efficiency to ensure greater sustainability (Hawkesford *et al*., 2013). To overcome this challenge only a multidisciplinary approach is likely to success (Parry & Hawkesford, 2012).

During the nineteen sixties, wheat yield increases were reached due to the exploitation of semi-dwarf wheat varieties (Reynolds & Borlaug, 2006b). The dwarfing genes led to more grains per m^2 and greater harvest index (HI), also increasing the amounts of N fertiliser used globally, which could be used without causing lodging (Hawkesford *et al*., 2013; HGCA, 2012; Reynolds & Borlaug, 2006b). As a result, wheat production became more intensified, resulting in increased food production for humankind through the end of the 20th century (Borlaug, 1971). However, global food security was never completly realised, particularly in developing countries (Blaustein, 2008; Reynolds & Borlaug, 2006a).

Regardless of the substantial increases in wheat yield in the last decades, further increase is still required to fulfil the demand of a growing population (Hawkesford *et al*., 2013) (e.g. 50% in the next few decades; Reynolds *et al.,* 2012). However, global wheat yields seem to be reaching a plateau in many countries, which could relate to HI already reaching its maximum (Brown, 2012), e.g. 0.50 for spring wheat (Reynold *et al*, 2009). In the UK, increases in wheat grain yield have been achieved due to genetic improvements, but at a rate of less than 0.1 tonnes ha^{-1} per year (Hawkesford *et al*., 2013). In order to accomplish the increasing yield needed, several national and international programmes have being created (e.g. 20:20 Wheat; G20-led Wheat Initiative; Wheat Yield Consortium). Further improvements will also require increases in total crop biomass and this will require further improvement in efficient use of the available resources (Long *et al*., 2006; Parry & Hawkesford 2010; Reynolds *et al*., 2012).

1.2.Problem statement and study aim

Farmers are facing increasing pressures to produce wheat that meets economic yield targets; specific nutrition and market requirements (Mercier & Hyberg 1995), while

making use of inputs in such a way that can ensure economic and environmental goals efficiently (DEFRA, 2011, 2014b; Hawkesford *et al.*, 2013).

As the awareness of combined ecological and economic costs of maintaining yields in intensive-input systems has grown, several studies have been concerned with the transition from conventional to organic agriculture systems (Clark *et al.,* 1999; Gomiero *et al.,* 2011; Hass *et al.,* 2001; Liu *et al.,* 2007; Pimentel *et al.,* 2005). However, organic production often results in lower yields, as a consequence often of greater weed and disease pressures and increasing soil nutrition deficiency (Moakes & Lampkin, 2011; Pridhanm & Entz, 2008; Ryan *et al.*, 2004). In the UK the classified organic land is decreasing, according to the National Survey produced by the UK Government Department for Environment, Food and Rural Affairs (DEFRA, 2014). In spite of a steady growth of the organic land since 2006, a decrease in the fully converted and in-conversion organic land was recorded from 2009 to 2013 by 11% and 80%, respectively (DEFRA, 2014). Such a decline in organic land is related in part to the reduction of the financial support to the organic sector by Government policies, as agri-environment payments in the UK are the lowest in the European Union accordingly to the Soil Association (2011).

Whilst accepting that organic farming is providing for a specialist niche food product market, the lower organic yields compared with conventional production systems together with a decrease in organic certified land, have made necessary a different approach to better combine cultural practices and the use of chemical and external inputs, so as to increase crop yield and making a better use of resources.

The overall aim of the investigation presented in this thesis is to study how the interaction between cultivation techniques, nitrogen fertilisation and legume-undersowing influence the ability of spring wheat to grow and develop. Further investigations consider treatment repercussions on the yield components that contribute to yield and grain quality. Towards increasing understanding of factors which influence crop development, essential soil processes, plant disease development and weed diversity.

1.3. Objectives of the study

The purpose of this study was to evaluate how a changing agronomy could support a more integrated crop management approach, by including combinations of external inputs and cultural practices. In order to also assess relationships between these management practices for both, increasing yields and a more profitable production cropping system.

The specific objectives of the study were:

1. To estimate the productivity of spring wheat intercropped with black medic (*Medicago lupulina* L.) and white clover (*Trifolium repens* L.) compared with sole wheat crop.
2. To evaluate the potential of black medic and white clover when undersown with spring wheat for weed suppression.
3. To determine the benefits that different soil cultivation techniques disturbance (conventional tillage, high intensity non-inversion tillage and low intensity non-inversion tillage) have on weed pressure and crop productivity.
4. To evaluate the effect of nitrogen nutrition on crop productivity and weed infestation.
5. To investigate nitrogen availability within all the interactions among components for spring wheat production.
6. To investigate weather patterns, in different growing seasons, affecting spring wheat production under the field site conditions.
7. To determine the profitability and energy consumption of the modified management practices for spring wheat production.

1.4. Thesis structure

Chapter 1 - Introduction. Brief overview of the justification of this study and outlining the aim and objectives examined.

Chapter 2 - Literature review. Review of the agricultural management practices, such as cultivation techniques, nitrogen fertilisation and undersowing, and how these determine

crop growth and development. This section also highlight challenges related to the intrinsic combination of factors affecting crop production.

Chapter 3 - Materials and methods. Reports the methodologies and techniques adopted in this study.

Chapter 4 - Core experiment – 2013. Influence of contrasting cultivation techniques, nitrogen fertilisation and legume undersowing in spring wheat. Reports outcomes of the core experiment during 2013 cropping season, and also provides a critical discussion of the influence of the management systems studied and the main conclusions.

Chapter 5 - Core experiment – 2014. Influence of contrasting cultivation techniques, nitrogen fertilisation and legume undersowing in spring wheat. Provides the outcomes of the core experiment performed during 2014 cropping season with critical discussion and main conclusions.

Chapter 6 - Effects of weather conditions on spring wheat performance following different cultivation techniques regimes. A meta-analysis of the effect of rainfall affecting spring wheat yield under contrasting cultivation techniques.

Chapter 7 - Economics and energy considerations for contrasting cultivation techniques, nitrogen fertilisation and undersowing in spring wheat. Illustrates the economic and energy consideration of the adoption of the agricultural management practices adopted.

Chapter 8 - General discussion and conclusions. A critical discussion of agricultural practices selected in this study is presented highlighting strengths and limitations. This section reaches the conclusions, and suggests implications of the study, with possibilities for further research.

CHAPTER TWO

Literature review

2.1. Cultivation techniques

Soil cultivation is considered one of the most important practices in agriculture due to its effect on the soil physical, chemical and biological properties (Wild, 1988). Cultivation techniques aim to prepare a suitable soil environment for seed emergence and plant growth. Ahn & Hintze (1990) define tillage as any mechanical or manual cultivation operations which create physical loosening of the soil, and according to Lal (1979) soil tillage is the alteration of the soil properties in order to modify soil conditions for crop production.

To obtain a more suitable medium for crop growth and development, soil manipulation by cultivation techniques can influence soil compaction, aeration and erosion; crop residues distribution into the soil; weeds and diseases suppression (Gajri *et al*, 2002) and soil N mineralisation (López-Bellido *et al.,* 2005; Silgram & Shepherd, 1999). Additionally, energy and labour costs for crop production can also vary depending on the cultivation technique adopted (Ozpinar & Cay, 2005).

In the UK, tillage systems can be categorised into two main classes: inversion tillage system also referred as conventional tillage, and non-inversion tillage also broadly known as conservation tillage (Davies & Finney, 2002).

2.1.1. Conventional tillage

Conventional tillage (ploughing) involves primary and secondary cultivation operations to prepare the seedbed (Gajri *et al*., 2002). Primary cultivation is the main operation consisting on the inversion of the soil by the use of mouldboard ploughs. Those used currently are mostly reversible and consist of a coulter frame with a series of mouldboards, forward rake points, vertical plates and tail pieces attached to the rigid plough frame (Soffe, 2003). Depending on soil type and cultivation speed, the mouldboards ploughs working depth is around 20 to 25 cm depth (Brassington, 1986).

This primary operation is often followed by secondary cultivations which creates a smooth seedbed by the use of a power harrow generally in conjunction with a seed drill (Bell, 1996; Soffe, 2003). A power harrow consists of almost vertical pair of tines, each one attached to a gear, which drives or is driven by adjacent gears, resulting in contra-rotating sets of neighbouring tines (Soffe, 2003). The harrows move rapidly across the soil surface leaving a level and smooth seedbed (Brassington, 1986). The combination of primary and secondary cultivations provide a regular soil surface which allow good seed-soil contact (Braunack & Dexter, 1989), and bury crop residues which can also disrupt weed, pest and diseases life cycles, giving better crop germination and growth conditions (Gajri *et al*, 2002).

However, several detrimental effects of continuous conventional tillage practices have been reported (Table 2.1). Despite these reported negative effects, the use of the plough is still justified by many farmers to loosen crusted and compacted soils, towards optimising yields, but in some cases its use may just be for ease of drilling (Morris *et al*, 2010).

Table 2. 1. Some detrimental effects of conventional tillage

Effect	Reference
Increase in soil erosion	El Titi (2003); Lal *et al.* (2007); Larson & Osborne (1982)
Increase in organic matter oxidation	Lal *et al.* (2007); Mitchell *et al.* (2004); Six *et al.* (2000)
Lower work rates	Akbarnia *et al.* (2010); Ozpinar & Çay (2005)
Increase in cost and energy-use	Akbarnia *et al.* (2010); Arvidsson (2010); Ozpinar & Çay (2005)

2.1.2. Non-inversion tillage

Non-inversion tillage systems have now become more widely used alternatives to conventional tillage on different soil types (IPCC 2014a, Kassam *et al.,* 2009), including heavy clays (Cannell & Hawes, 1994; Holland, 2004), on around 15% of the arable land in Europe (Jones *et al*., 2006). In the UK, conservation tillage systems involve the use of tines and disc harrows without inverting the soil, but incorporating

much of the crop residues in the top-soil layers although maintaining a proportion on the soil surface (Carter *et al*., 2003; Peigné *et al.,* 2007; Soane *et al*., 2012). Tines can be found in different shapes and angles, from straight to curve and either fixed or moving with crumblers attached to mounted sections or front boards (Christian, 1994). Tines are designed to remove any compacted layer by lifting and shattering the soil and to breakdown residues (Morris *et al*, 2010), and are often followed by disc harrows at a shallow depth of around 12 to 15 cm, depending upon soil type and cultivation speed (Soffe, 2003). Disc harrows comprise two or four adjustable axles with concave discs mounted along its length (SMI, 2003). Axles are angled for forward motion. The front axle discs cut and throw soil outwards, while rear axle discs throw soil inward (Soffe, 2003). Press wheels are usually attached at the rear of the cultivator in order to level and firm the soil surface prior to seed drilling (Morris *et al*., 2010). It is often required for drilling, the use of a high output cultivation drill combined with tines and discs ahead of the seed coulter in order to facilitate seed depth and emergence (Bell, 1996).

Non-inversion tillage creates seedbed and soil environment conditions that allow seed germination with less soil movement and inversion (Cannell, 1994). Table 2.2 summarises reported effects of non-inversion tillage.

Table 2. 2. Some reported non-inversion tillage effects

Effect	Reference
Reduction of soil erosion	Carter (1991); Hussain *et al.* (1999); López *et al*. (1996)
Improved soil moisture retention	Carter (1991); Hussain *et al.* (1999); Sharma *et al*. (2011)
Reduction of organic matter oxidation	Morris *et al.* (2010); Soane *et al.* (2012)
Increase in soil microbial activity	Mitchell *et al.* (2004); Morris *et al.* (2010); Soane *et al*. (2012)
Reduction of costs and energy-use	Jones *et al*. (2006); Knight (2004); Sanchéz-Girón *et al.* (2004); Triplett & Dick (2008)
Higher work rates	Jones *et al*. (2006); Triplett & Dick (2008)

2.2. Cultivation techniques and soil properties

Variations of tillage intensity commonly alter the soil physical, chemical and biological properties resulting in changes of the soil functional quality, as widely reported (Aziz *et al.*, 2009; Celik *et al.*, 2011; Ding *et al.*, 2011).

2.2.1. Soil physical properties

Around 50% of the crop root mass grows in the seedbed created by the tillage operations (Finney & Knight, 1973). Tillage effects on soil physical properties are highly important therefore, to the essential crop growth and development. Differences in tillage intensity can temporally change soil physical conditions (Rasmussen, 1999; Tebrügge & Düring, 1999). If the soil is too hard, too dry, lacks of oxygen or its temperature is far from optimal, it can limit root growth (Bengough *et al.*, 2006; Kaspar & Bland, 1992). However, these changes depend on soil type, climate conditions and the type and extent of previous tillage systems adopted (Rhoton, 2000).

Some of the most important soil physical properties of the seedbed created by the cultivation techniques practices are soil bulk density and soil penetration resistance (Cassel, 1982). Soil bulk density influences soil water and air dynamics and also how crop roots grow (Unger & Cassel, 1991). The immediate tillage effect is loosening the soil which then decreases the bulk density. However, this effect is not permanent and it can be reduced or even reversed with subsequent events such as continuous soil disturbance or increasing rainfall conditions. Among cultivation techniques, conventional tillage reportedly presents lower soil bulk density compared with non-inversion tillage systems, especially in the upper 0-15 cm soil layer (Kaspar *et al.*, 1992; Munkholm *et al.*, 2003; Stokes *et al.*, 1992). However, several other studies reported higher bulk density under conventional tillage compared with non-inversion tillage systems (Griffith *et al.*, 1977; Lal, 1979; Sharma *et al.*, 2011). This is mainly related to the high presence of residues under non-inversion systems which reduce the bulk density, particularly in relatively compacted soils (Ghuman & Sur, 2001). Such variable results highlight the widely contrasting impact differences of tillage and their dependence on environmental conditions and soil type. Moreover, alterations of bulk

density by tillage systems tend to be maximased after initial cultivation practices are undertaken, but might possibly decrease with time or even become insignificant at the end of the cropping season (López *et al*., 1996; Pelegrin *et al*., 1990).

Cultivation techniques can also affect the soil total pore space arrangement which is inversely correlated with bulk density (Carter & Ball, 1993; Guérif *et al*., 2001). Reductions in total pore space can indicate increases in soil penetration resistance. This is especially relevant for crop development as it can affect the crop root growth (Cassel, 1982). Atwell (1993) reported that a penetration resistance greater than 2MPa can potentially reduce root growth. However, a penetration resistance of 1.5MPa has been used as a reference to assess tillage practices impact on soil loosening (Carter, 1988). Soil penetration resistance reportedly increases when increasing soil depth, mainly due to increases in soil particles friction (Bradford, 1986; Campbell & O'Sullivan, 1991; Grant & Lafond, 1993). Differences between cultivation techniques on penetration resistance have been widely studied. Non-inversion tillage reportedly presents higher penetration resistance in the upper 15cm soil layer than conventional tillage (Aikins & Afuakwa, 2012; Grant & Lafond, 1993; Munkholm *et al*., 2003; López *et al*., 1996). This has also been commonly observed particularly in soils with poor structure and low soil organic matter (Hill, 1990). However, cultivation effects on soil penetration resistance is often reported to be temporal and dissipating after several years as the soil recover its former state, as reported by several studies (Campbell & Henshall, 1991; Franzluebbers *et al*., 1995; Martinez *et al.*, 2008). Penetration resistance also decreases when soil moisture content increases, as water absorption weakens connections between soil particles (Marshall & Holmes, 1988).

Soil moisture content reportedly increases with increasing soil residues cover. Such residues enhance soil structure improving infiltration and protecting the soil from evaporation and runoff (Allmaras *et al*., 1977; López *et al*., 1996). Greater presence of plant residues on the soil surface under non-inversion tillage, therefore, results in higher soil moisture compared with conventional tillage, as widely reported (De Vita *et al*., 2007; López *et al*., 1996; Sharma *et al*., 2011). However, differences in soil moisture content between tillage practices are also highly dependent in weather pattern particularly rainfall, as reported by De Vita *et al*. (2007).

2.2.2. Soil chemical properties

Changes in tillage intensity can also potentially influence soil reaction (pH), organic matter stratification and nutrient distribution (Staley, 1999; White, 1990), although this also depends on environmental conditions and soil type (López-Fando & Pardo, 2009; Thomas *et al*., 2007). Several authors (Hickman, 2007; Houx III *et al*., 2011; Vijaya Bhaskar *et al*., 2013a) reported decreases in soil pH with less tillage intensity. This soil acidification under non-inversion tillage systems is related to the breakdown of crop residues on the soil surface, which possibly result in organic acids accumulation, causing lower soil pH (Blevins *et al*., 1977). Additionally, without soil inversion, variations on soil pH are slow, being influence by slow movement of carbonic acid (H_2CO_3) through the soil profile (López-Pando & Pardo, 2009).

2.3. Cultivation techniques and soil nitrogen availability

Soil movement created by the cultivation techniques reportedly results in temporary increase of the availability of soil mineral nitrogen (SMN). This occurs by modifications of the soil environment, such as water content and temperature, and increasing growth and activity of soil fauna promoting organic matter oxidation (Silgram & Shepherd, 1999; Wild, 1988). However, the SMN availability created by tillage operations varies with operations timing and weather conditions during and after cultivation performance, as widely reported (El Titi, 2003; Kapusta *et al*., 1996; Radford *et al*., 1992). Additionally, Silgram & Shepherd (1999) reported that such tillage effects are often noticeable just for a few weeks. The presence and nature of crop residues incorporated or left on the soil surface also affects the availability of SMN. Crop residues with high C/N ratio cannot provide enough N to the microbial population, promoting rapid N-immobilization and limiting its availability to the subsequent crop (El Titi, 2003; Silgram & Shepherd, 1999).

Non-inversion tillage systems reportedly can result in lower SMN than conventional tillage due to transitory N limitations (Al-Khasi *et al*., 2005; Braim *et al*., 1992; McConkey *et al*., 2002; Silgram & Shepherd, 1999). This is perhaps the result of lower organic matter oxidation in spring, autumn and winter but increased mineralisation in

summer (Blevins & Frye, 1993; Riley *et al.,* 1994; Schomberg *et al*., 1994). Additionally, lower SMN has often been related to higher N-immobilization and nitrification of the crop residues (López-Bellido *et al*., 2013; Soane *et al.,* 2012). However, increases in SMN availability by increasing tillage intensity do not necessary support greater crop productivity (Greenwood, 1982), due to the increasing risk of leaching which can result in nitrates being less available during high crop demand (Silgram & Shepherd, 1999).

2.4. Cultivation techniques and weed suppression

Weeds can provide food and habitats for a range of beneficial organisms which can also benefit the crop if weed population is low (Cussans, 1968; Storkey, 2006). Above critical thresholds, weeds can compete and reduce the main crop yield and quality, which make weeds a major factor affecting cereal production (Froud-William *et al.,* 1983b; Marshall *et al.,* 2003). Weed occurrence is significantly influenced by the cultivated crop species, crop rotation, tillage practices, timing and type of weed management, and primarily by environmental factors, such as weather conditions, location and season of the year (Derksen *et al*., 1995; Shrestha *et al*., 2002; Tuesca *et al*., 2001).

Tillage practices often modify weed abundance and species composition in crops (Ball & Miller, 1993; Froud-Williams *et al*., 1981; Hakansson, 2003). Tillage affects the weed populations by changing the seed distribution both vertically and horizontally, affecting the seeds viability, emergence and seedling survival. Also by dismembering vegetative structure of perennial weeds, and thereby stimulating bud growth and depleting their food reserves (Clements *et al*., 1996a; Streit *et al*., 2002; Swanton *et al*., 2000). Inverting the soil reportedly buries most seed initially present in the soil surface, but it can also relocate buried seeds back to the topsoil (Colbach *et al*., 2006; Hakansson, 2003). Without soil inversion, weed seeds are maintained on the surface and distributed less down the soil profile due to less soil movement (Ball, 1992; Froud-Williams *et al*., 1983a).

Among weed species, it has been widely reported that increasing tillage intensity increases broadleaf weed species frequency but decreases grass weeds (Froud-Williams *et al*., 1983b; Tuesca & Puricelli, 2007; Tuesca *et al*., 2001). Grass weed species are also highly susceptible to mechanical disturbance, which restricts their presence under conventional tillage. Limited soil disturbance under non-inversion tillage systems can result commonly in a greater incidence of grass weeds (Hakansson, 2003). Additionally, non-inversion tillage systems have also been related to increases in grass weeds, such as *Poa* spp and *Alopecurus myosuroides* (Froud-Williams *et al*., 1983b), which are able to germinate on a soil surface covered by residues that can maintain moisture (Mester & Buhler, 1991; Tuesca & Puricelli, 2007). Generally, broadleaf weed seeds have greater longevity and marked dormancy; with annual inversion of the soil bringing to the soil surface dormant buried seed allowing their germination (Froud-Williams *et al*., 1983b). Some broadleaf species, such as *Chenopodium album* L., have also been linked more to conventional tillage due to the accumulation of residues on the soil surface under non-inversion systems creating more shady conditions, reducing those species ability to germinate (Teasdale, 1993).

Tillage systems also affect weed population by altering soil temperature and moisture required by many weed species to break dormancy (Thompson *et al*., 1977). Temperatures above or below the optimum range for germination, can possibly decrease seeds germination whilst, some species germinate better under alternating rather than constant temperatures (Vincent & Roberts, 1977).

In terms of weed species diversity, soil disturbance created by cultivation often prevents one species becoming dominant within the community and can, therefore, increase diversity (Cardina *et al.,* 2002; Clark *et al.,* 2007; Sousa, 1984).

2.4.1. Cultivation techniques and herbicide-use

Historically, the inclusion of herbicide applications reduced the important of cultivation techniques as a major mean of weed control (Froud-Williams *et al*., 1983b). However, an increasing number of weeds showing resistant to a wide range of herbicide active ingredients have been identified in the UK, particularly black grass (*Alopecurus*

myisuroides), wild oat (*Avena fatua L.*) and Italian ryegrass (*Lolium perenne L.*) (Davies & Finney, 2002). Herbicide resistant weeds are increasing interest in the complementary use of cultivation techniques and herbicide applications as more integrated weed control strategy (Finch *et al.*, 2014). For instance, the use of pre-emergence herbicides can exert beneficial weed control under non-inversion tillage systems with most of the weeds remaining in the soil surface before the establishment of the crop (Calado *et al.,* 2010). In addition, several authors report that herbicide application can reduce possible differences between tillage for weed suppression (Derksen *et al.*, 1995; Vijaya Bhaskar *et al.*, 2014b).

However, herbicide's effectiveness for weed control can also reportedly be reduced by residues left on the soil surface (Buhler, 1995). Sadeghi *et al.* (1998) found 70% of herbicide interception by crop residues, reducing its subsequent suppression effect on weeds. Additionally, the herbicide type and application time can also influence the efficacy of controlling weeds (Derksen *et al.*, 1995; Soane *et al.*, 2012; Streit *et al.*, 2002). For example, Anken *et al.* (2004) reported that the broad-spectrum systemic herbicide such as glyphosate reduces its effectiveness under low temperatures and also frequent rainfall condition after application. Underlighing cultivation techniques influences on weed control are important in selecting an effective herbicide, with the associate cost also affecting the crop enterprise profitability (Sayili *et al.*, 2006).

2.5.Cultivation techniques and diseases

The effects of tillage on plant disease can vary depending on crop type, biology of the pathogen, soil type and prevailing environmental conditions (Bailey & Duczek, 1996; Conway, 1996). Cultivation techniques modify the soil environment affecting pathogens, but can also change the distribution of crop residues which for many pathogens are primary inoculum source (Jenkyn *et al.*, 2004). Under non-inversion tillage, higher residues can provide substrate for residue borne pathogens but, also modifies soil temperature and moisture encouranging diseases (Bockus & Shroyer, 1998; Sutton & Vyn, 1990; Watkins & Boosalis, 1994). If the contaminated residues are destroyed and buried by ploughing the inoculum is also destroyed, but if residues are

left undisturbed the pathogen survives resulting on the disease development (Sumner *et al.*, 1981). This is the case of some cereal diseases presented in Table 2.3, which are favoured by non-inversion tillage, while others occur more frequently under conventional tillage (Table 2.3).

Table 2. 3. Some reported cereal diseases favoured by different cultivation systems

Non-inversion tillage	Reference
Gaeumannomyces graminis var. *tritici* (take-all of wheat)	Ennaifar *et al.* (2005); Sumner *et al.* (1981)
Pyrenophora tritici repentis (tan spot of wheat)	Sumner *et al.* (1981)
Mycosphaerella graminicola (leaf blotch)	Vijaya Bhaskar *et al.* (2014a)
Rhizoctonia solani (rhizoctonia stunt)	HGCA (2008a); Sumner *et al.* (1981)
Conventional	
Bipolaris sorokiniana (common root rot)	Bailey & Duczek (1996); Conway (1996)

2.6. Cultivation techniques and crop yield

Crop yield is affected by interactions of the crop with such factors as the growing environment, soil type and tillage intensity (Rasmussen, 1999), although interactions are not always consistent nor predictable (Jones *et al.*, 2006). Cultivation techniques effects on the soil environment affect crop growth and development and also final crop yield. Several studies report crop yields under conventional tillage are either higher or comparable to those from non-inversion tillage (Gruber *et al.*, 2012; Rasmussen, 1999; Soane *et al.*, 2012; Vijaya Bhaskar *et al.*, 2013b). Table 2.4 summarise reported detrimental effect of non-inversion tillage resulting in lower yield compared with conventional tillage. Mixing and/or incorporation of the residue in the soil allows better seed-soil contact, increasing germination and crop establishment and resulting in better final yield under conventional tillage (Table 2.4)

Table 2. 4. Detrimental effects of non-inversion tillage on final grain yield

Effect	Reference
Poor crop establishment	Hemmat & Taki (2001); Vijaya Bhaskar *et al*. (2013b); Wilkins *et al*. (1989)
Higher weed and disease pressure	Gruber *et al*. (2012); McConkey *et al*. (1996); Vijaya Bhaskar et al. (2013b)
Higher soil penetration resistance	Cassel *et al*. (1995); Rasmussen (1999); Vyn & Raimbault (1993)
N inmobilization	Chen *et al*. (2007); López- Bellido *et al*. (2013); Wang *et al*. (2012); Wang *et al*. (2015)

The effect of non-inversion tillage on crop yield is also highly variable depending on weather conditions, as reported by several authors (e.g. De Vita *et al*., 2007; López-Bellido *et al*., 1998; Ordoñez-Fernández *et al*., 2007). Such variations are partially associated with modifications in soil moisture content, e.g. greater water storage during dry periods (Bonfil *et al*., 1999). Carr *et al*. (2006) found almost 40% greater yield under non-inversion than conventional tillage, attributed to the greater soil moisture holding capacity in alleviating crop water stress.

Soil type plays a very important role on the performance of the cultivation techniques and their effect on the final crop yield. Knight (2004) reported that non-inversion tillage yielded lower than conventional tillage in two of three years under clay soil while, non-inversion tillage resulted in the greatest yield in three years on a light chalkland soil. Kumar *et al*. (2013) also reported greater yield under non-inversion compared with conventional tillage in a sandy loam soil, attributed to better soil moisture content under non-inversion treatment. In contrast, Munkholm *et al*. (2003) concluded that yield decreased under non-inversion tillage on light-textured soils mainly due to greater soil compaction in a moist climate. Repeated tillage systems effects on yield are sometimes contradictory and depend on site-specific factors, such as soil type, environmental conditions and previous management history (Arvidsson *et al*., 2013; Morris *et al*., 2010; Rasmussen, 1999).

2.7.Cultivation techniques and grain protein

For the wheat industry, grain protein is one of the main factors being sought (Wall *et al.*, 1979), with bread making potential largely determined by the quantity and quality of the grain protein (Hruskova & Famera, 2003). Several factor interactions are reported to influence grain quality, including cultivar, soil type, grain storage conditions, N availability and environmental conditions (Blumenthal *et al.*, 1991; Borghi *et al.*, 1997; De Vita *et al.*, 2007; Gooding & Davies, 1997).

Cultivation techniques effects on grain protein are mainly through modifications of soil moisture and soil nitrate content (López-Bellido *et al.*, 1998). It has been stated that an excess of soil moisture can lead to a decrease in grain protein content (Robinson *et al.*, 1979), while water stress increases protein content (Rao *et al.*, 1993; Terman *et al.*, 1996). Conventional tillage can result in higher protein content compared with non-inversion tillage systems, mainly due to higher N availability (De Vita *et al.*, 2007; López-Bellido *et al.*, 1998). In contrast, others studies reported no significant differences between tillage treatments on grain protein content (Bassett *et al.*, 1989; Cox & Shelton, 1992).

2.8.Nitrogen fertilisation and plant growth

A high amount of N is required by crops as it is an essential constituent of chlorophyll, and a major component of proteins and enzymes which catalyse essential reactions for the crop life (Blevins, 1989). Wheat development can be influenced by N applications mainly in four difference ways presented in Table 2.5.

These N fertilisation influences are interrelated even though they might not always be beneficial. For instance, it has been reported that increases in crop aboveground biomass might lead to increases in ears number per plant with high grain number. This can result in high grain yield while harvest index (the ratio of harvested grain to the total aboveground dry matter) stays unchanged (Cabrera-Bosque *et al.*, 2009; Cossani *et al.*, 2009).

Table 2. 5. Nitrogen fertilisation effects on cereal plant growth and development

Effect	Reference
Increase in the size and duration of canopy growth	Gooding & Davies (1997); Ottenson *et al.* (2008)
Affects individual plants within the crop stand, e.g. determining tillers survival which will sustain ears	Greenwood (1982); HGCA (2008b); Ottenson *et al.* (2008); Sarandon & Gianibelli (1990)
Produces heavy stems potentially increasing losses by lodging and disease attacks	Hay & Walker (1989); HGCA (2008b); Gerba *et al.* (2013)
Determines grain quantity and quality	Gooding & Davies (1997); Greenwood (1982); Smith *et al*. (1990)

N uptake by a crop and its effect on annual yields are often variable even on the same site and when the N available fulfils the crop demand. This considerable variability is due to the vegetative growth relative to grain yield and how it responds to water and nutrient availability, crop management and climate conditions (Ferguson, 1967; Hay & Walker, 1989; López-Bellido, *et al*., 1998). For instance, Pearman *et al*. (1977) observed a lack of N effect on grain yield attributed to lower autumn precipitations which reduced any potential N leaching leaving high level of residual N in the soil. This was also reported by several other studies (Barraclough *et al*., 1989; Cabrera-Bosque *et al*., 2009; López-Bellido *et al*., 1998) while others have also reported decreases in yields with increasing N application (Cossani *et al*., 2009; Fois *et al*., 2009; Gooding & Davies, 1997). However, N application often increases grain yield (Abad *et al.,* 2005; Brennan *et al.,* 2014; Halvorson *et al.,* 2001; Raun *et al.,* 2010).

Regarding grain qualities, it has been suggested that N application improves the specific grain weight (Pushman & Bingham, 1975). However, several studies report negative effect of N fertiliser on specific grain weight mainly by increases in the grains number per ear (López-Bellido *et al*., 2000; Rasmussen *et al*., 1997; Smith & Davies, 1990).

2.8.1. Nitrogen-use and nitrogen-use efficiency

In the UK, wheat crops generally need large amount of available N in order to produce high grain yields and high protein content (Barraclough *et al.,* 2010; Greenwood, 1982). In order to optimise resources use, it is essential to understand the complex inter-relationship between N availability, uptake and utilisation during crop growth (Barraclough *et al.,* 2010).

N-use efficiency (NUE) in cereal crops is defined as grain dry matter yield per unit of available N from the soil and/or fertiliser (yield efficiency) (Moll *et al.*, 1982; Le Gouis *et al.*, 2000),

$$\text{NUE (kg kg}^{-1}) = \frac{\text{Grain yield}}{\text{N available}} = \text{NUpE x NUtE}$$

NUE can be further divided into two primary components: (1) N uptake efficiency (NUpE); the efficiency with which the plant absorbs N from the soil, and (2) N utilisation efficiency (NUtE); the efficiency with which the absorbed N is used to produce grain dry matter (Moll *et al.*, 1982; Le Gouis *et al.*, 2000),

$$\text{NUpE} = \frac{\text{Total plant N uptake}}{\text{N available}} \qquad \text{NUtE} = \frac{\text{Grain yield}}{\text{Total plant N uptake}}$$

Therefore, improvements in either NUpE or NUtE could improve NUE.

In crops generally, including cereals, the full recovery of N fertilisers is never achieved mainly due to the dependence on several factors such as soil type, climate conditions, crop variety, SMN availability, and the nature of the inorganic fertiliser applied (Burger & Jackson, 2004; Schulten & Schnitzer, 1998). In the case of wheat, Ladha *et al.* (2005) reported that the average recovery of N fertiliser is around 54%. In a study on winter wheat grown in eastern England by Powlson *et al.* (1992), wheat recovered an average of 68% of the N fertiliser applied, while 18% was retained in the soil and 14% lost by leaching and de-nitrification. The efficiency in the use of the N absorbed by the plant to produce grain yield is highly dependent on genotypic variations but also by the response to the environmental conditions (Hirel *et al.,* 2007).

The efficiency in the partitioning of aboveground biomass per unit of N uptake to the grain (NUtE) is an important process influencing yield quantity and grain quality (Le Gouis *et al*., 2000; Ortiz-Monasterio *et al*., 1997; Simpson *et al*., 1983). From the same N uptake, crops with higher NUtE will produce higher yields or the same yield with a lower N uptake.

The N contained in the aboveground crop can count as much as 50 to 80% of the grain N content at harvest (Cox *et al*., 1985; HGCA, 2008b; Sarandon & Caldiz, 1990; Xu *et al*., 2005) depending on the variety and environmental conditions. Palta *et al*. (1993) reported increases in N remobilisation efficiency from the vegetative organs to the grain in conditions of water stress during grain filling period, as the plant needs to make better use of its N accumulated at anthesis. Conversely, N remobilization during grain filling can be reduced by foliar diseases (Dimmock & Gooding, 2002) and high temperatures (Heitholt *et al*., 1990) due to acceleration of senescence of the vegetative parts (Gooding & Davies, 1997).

In other words, NUE can sometimes decrease with N application (Campbell *et al*., 1977; Clark *et al*., 1990; Sieling *et al*., 1998) due to wrong application practices such as high amounts and/or wrong timing. If the amount of N applied is too high, the plant might not be able to take-up all decreasing NUpE, if so the N uptake may be utilised less efficiently (NUtE), and hence less NUE. In addition, NUE highly depends upon the response to water availability during the growing season (Hatfield & Prueger, 2004; Semenov *et al*., 2007). During lower water availability, NUE decrease is mainly due to less N available for the crop. At high water availability, in contrast, the N available could be lost by leaching.

2.8.2. Nitrogen fertilisation and grain protein

Grain protein is often considered the most important singular criterion in defining grain quality specifically for the bread making industry. However, grain protein content is determined by genotype (Johnson *et al*., 1985; Stoddard & Marshall, 1990) and influenced by growing environmental conditions (Blackman & Payne, 1987; Rao *et al*.,

1993). N availability and distribution is one of the major determining factors of the grain protein concentration (Fowler & Brydon 1989; Hirel *et al*., 2007; Hunter & Stanford, 1973; Olson *et al*., 1976). N application can also improve grain protein, commonly showing a linear response in a wide range of growing environments (Gao *et al.,* 2012; López-Bellido *et al*., 1998; López-Bellido *et al*., 2001). However, weather conditions throughout the growing season play an important role highlighting any possible positive or negative effects of N fertilisation on grain protein content. Applying N with appropriate soil moisture content mainly leads to increases in yield with limited effect on grain protein (Campbell *et al*., 1977; Clark *et al*., 1990; Smith and Gooding, 1999), whereas water stress reduces crop yield, while it may increase grain protein (Campbell *et al*., 1977; Terman *et al*., 1996). For instance, Kosmolak & Crowle (1980) reported an increase of 1% of the protein content with an application of 26 kg N ha^{-1} to a crop yielding 2.5 t ha^{-1}; whereas Penny *et al*. (1978) reported the same increase of protein when only 46 kg N ha^{-1} was applied but to a crop yielding 5 t ha^{-1}, with this variation mainly attributed to water availability across the growing season.

Increasing soil moisture can potentially reduce grain protein content, particularly if this occurs prior the grain filling due to the dilution of early N reserves by increases in vegetative growth (Smith & Gooding, 1999). Conversely, rainfall events during the summer can have positive effects on grain N particularly due to wetting / drying cycles of the soil affecting N mineralisation, beside the increase of rainfall at this point possibly increases diseases levels which reduces yields and therefore increasing the grain protein (Farrant, 1972; Smith *et al*, 1990). In other words, the effect of the interaction between N application and predominant weather conditions on the protein content can also depend on the crop developmental stage.

2.8.3. Nitrogen fertilisation and weeds

Competition between plants is highly dependent on many factors including availability of nutrient, especially N (Sweeney *et al*., 2008). Weeds can be directly influenced by N fertilisation, but also indirectly by increasing crop competitiveness against weeds. Crop ability to suppress weeds is increased by N application, mainly by promoting faster

growth which increases the competition for resources, resulting in the reduction of weed species number and biomass (Grundy *et al*., 1993; Jørnsgård *et al*., 1996). Conversely, weed growth can response positively to N fertilisation possibly due to differential NUE compared with the crop (Di Tomaso, 1995; Sheibani & Ghadiri, 2012). The response to N fertilisation also greatly differs among different weed species (Iqbal & Wright, 1997). In a long-term experiment, Moss *et al*. (2004) reported that *Stellaria media* L. was highly favoured by N-rich conditions while other species such as *Medicago lupulina* L. and *Equisetum arvense* L. were highly disadvantaged. Iqbal & Wright (1997) also reported that the relative competitive abilities of *Sinapsis arvensis* L. were greater than a wheat crop when 120 kg N ha^{-1} was applied, while *Phalaris minor* Retz. was less competitive under the same conditions. Jørnsgård *et al*. (1996) observed that *Lamium* spp and *Veronica* spp had lower N optima than wheat.

2.9.Intercropping

Liebman & Dyck (1993) defined intercropping as spatial diversification of cropping systems by growing two or more crop simultaneously. This practice has been known to improve soil fertility, especially in the case of leguminous crops cropped with non-legumes crops (Fujita *et al.,* 1992; Shafi *et al.,* 2007; Thorsted *et al.,* 2006). The ability of legumes to fix atmospheric N represents a valuable source of organic N by utilising their nodulated-roots and residues (Anil *et al*., 1998; Bakht *et al.,* 2009; Giller, 2001; Giller & Wilson, 1991; Kumar & Goh, 2002). However, the amount of N fixed can vary with the legume species, environmental conditions and crop management (Hamdi, 1995).

Intercropping is a practice widely used in developing countries as a way of increasing crop production per land area when capital investments are limited (Dakora 1996; Francis, 1986; Machado, 2009). However, interest in the use of intercropping in developed countries has also increased as a potential way to maintain or increase crop production while reducing fertilisers and pesticide use (Horwith, 1985; Machado, 2009).

2.9.1. Undersowing

In the UK, intercropping is mainly in the form of undersowing (Hartl, 1989) which consists of growing two or more crops sharing the same area for a part of their life cycle (Duncan & Schapaugh, 1997; Wallace *et al*., 1996). For instance, perennial legumes can be sown either with winter or spring sown cereal crop in the spring in order to develop a subsequent ley to avoid a period of bare ground (Hartl, 1989). Legumes add potential benefits to the intercropping system such as improvement of soil fertility by fixation and N release (Badaruddin & Meyer, 1990; Hauggaard-Nielsen *et al*., 2001).

Other potential benefits of undersowing is the suppression of weed, pest and diseases although it can also vary depending on the species grown, biomass production, time of sowing, harvest management and prevalent environmental conditions (Badaruddin & Meyer, 1990; Hartwig & Ammon, 2002). Weed suppression by the intercrop is mainly by the reducing the available space for weeds to germinate and grow, and by enhancing competition for resources such as light and nutrients (Anil *et al*., 1998; Liebman, 1986; Liebman & Dyck, 1993). Banik *et al*. (2006) and Hauggaard-Nielsen *et al*. (2003) reported greater suppression of weeds under intercropping over monocrops, mainly due to higher interspecific competition for resources and complementarity between intercrop species in improving their competitive abilities against weeds. Additionally, reduction in the incidence of pests and diseases by intercropping compared with monocropping has been reported (Hiltbrunner *et al*., 2002; Teasdale, 1996; Theunissen, 1997; Vilich-Meller, 1992).

Undersowing can also affect soil quality by covering the soil and reducing N leaching, while its biomass adds organic matter (Duda *et al*., 2003; Hartwig & Ammon, 2002). This addition of organic matter by the undersown species can improve the soil structure and can also reduce soil compaction reducing soil deterioration (Bristow & Horton, 1996; Teasdale & Mohler, 1993). However, undersowing can lead to competition between the crops growing together (Vandermeer, 1989) which can result in a decrease in growth, development (Crawley, 1997) and final yield of the main crop (Clements & Williams, 1967).

2.9.1.1.Undersowing effects on yield

Interactions among plant species inside the intercropping system occur during the growth process as the plants exploit the same resources (Vandermeer, 1989), which generally creates competition (Andersen *et al*., 2004; Hauggaard-Nielsen *et al*., 2001). This interspecific competition for resources commonly results in intercrop yields intermediate to that of the sole crop (Hauggaard-Nielsen *et al*., 2001; Thorsted *et al.,* 2006). Competition for resources can be reduced by manipulating the initial advantage of one of the crops inside the intercropping system through delaying understorey crop sowing, or by increasing the seed rate of the main crop (Andersen *et al.,* 2007). Charles (1958) reported, for instance, yield reduction in a cereal crop when the understorey crop was sown at the same time as the main crop. No reduction was observed when the understorey was sown when the main crop was already well established.

Nevertheless, in some cases the intercrop can enhance the productivity of the system (Fukai & Trenbath, 1993; Vandermeer, 1989). The cereal yield advantage of undersowing has been reported to be in part due to vigorous growth of the undersown species, which suppress weeds without affecting the main crop. In the case of undersown legume by enhancing the main crop N uptake (Brennan & Smith, 2005; Hauggaard-Nielsen *et al*., 2008; Zhang & Li, 2003).

2.9.2. Cereal-legume intercropping

Growing a cereal crop with a legume is the most common type of intercropping (Francis, 1989). However, it is important to consider that the species should have a synergistic effect with each other and no antagonistic interactions. When using legumes it is important to acknowledge the time at which the leguminous plants are releasing the previously fixed N, and when the cereal crop is capable of utilising (Charles, 1958). Generally, legume swards have to be ploughed in order to release N and then followed by a cereal crop to take up the resultant N. Species such as white clover (*Trifolium repens* L.) recovers and spreads rapidly following suppression due to its prostate and stoloniferous growth, being suitable for this practice (Jones, 1992). However, negative

effects have been observed when incorporating more than one crop in a cropping system (Pridham & Enz, 2008). Table 2.6 shows detrimental effects of intercropping resulting in lower cereal yield. Conversely, several studies reported potential benefits of the incorporation of legumes in a continuous arable cropping system without compromising the cereal grain yield (Table 2.6).

Table 2. 6. Adverse and beneficial effects of legume intercropping on cereal productivity

Detrimental effects	Reference
Competition for resources between crops	Thorsted *et al*. (2006); Jones & Clements (1993)
More land to produce the same yield than monoculture (greater land ratio)	Lithourgidis *et al*. (2011); Ofori & Stern, (1987); Reynols *et al*. (1994)
Beneficial effects	
Suppresion of weeds	Haymes & Lee (1994); Thiessen-Martens *et al*. (2005); Walker *et al*. (2011).
Increase N availability to main crop	Känkänen *et al*. (2001); Thiessen-Martens *et al*. (2005); Walker *et al*. (2011).

In cropping systems with external input such as N fertiliser, legume-cereal intercrops reduce their advantages over cereal only crops (Ghaley *et al*., 2005; Jensen, 1996; Ofori & Stern, 1987). This may relate to the increase of competitiveness of wheat adversely affecting the legume intercrop (Gooding & Davies, 1997), and the negative responses of legumes to N fertilisation (Moss *et al*., 2004).

In summary, the success of cereal-legumes intercrops depends on the development and maintenance of the desirable balance of the components (Clements *et al*., 1994b).

2.9.2.1.*Undersowing effect on grain protein*

The response of cereal grain protein when intercropped with legume species is highly variable (Berry *et al*., 2002; Jones & Clements, 1993). Several authors reported greater grain protein content of the intercropped cereal primarily due to the complementary use of resources by the intercropped species (Hauggaard-Nielsen *et al*., 2001; Jensen 1996;

Lauk & Lauk, 2008). Although this is thought to be related to the lower competitiveness of the legume crop for soil N and competition for resources such as light, thus limiting total cereal biomass production (Gooding *et al*., 2007; Hauggaard-Nielsen *et al*., 2006).

CHAPTER THREE

Materials and methods

The methods and techniques used in the present study were consistent between experiments; and are included in this chapter to avoid repetition. When methodologies differ or additional information is required, this will be given in the appropriate chapter.

3.1. Experimental site

Field experiments were initiated in March 2013 (Core experiment I) and March 2014 (Core experiment II). The field experiments were conducted on Evesham soil series, with characteristics shown in Table 3.1., at the Royal Agricultural University's Harnhill' Manor Farm (NGR SP 075 006), near Cirencester, UK, situated at 51° 42'N latitude, 01° 59'W longitude, at an altitude of 132 m above sea level. Soil texture was clay with a soil pH around neutral and initial soil mineral nitrogen (SMN) Index of 0 (Table 3.1).

Table 3. 1. Initial physiochemical properties of the experimental site

Parameters	Values	Parameters	Values	Index
pH	6.90	SMN (kg ha^{-1})	25.33	0
% Sand	22.59	P (mg l^{-1})	8.00	1
% Silt	37.48	K (mg l^{-1})	208.67	2
% Clay	39.93	Mg (mg l^{-1})	105.27	3

Following spring wheat harvest on 22 August 2012, broad-spectrum systemic herbicide – glyphosate [*N*-(phosphonomethyl)glycine], was applied at a rate of 4 l ha^{-1} across the entire experimental site (2.7 ha). After herbicide application, white mustard (*Sinapsis alba* L. cv. Tilney) was broadcasted over existing soil cover to grow over the winter 2012 (Plate 3.1). White mustard was used as a break crop to help to reduce infections of take-all disease (*Gaeumannomyces graminis* var. tritici) (HGCA, 2006; Vijaya Bhaskar, 2014). The cropping system history is summarized in Table 3.2.

Plate 3. 1. White mustard over existing soil cover. Winter 2012

Table 3. 2. Cropping systems used in the site from 2007 to 2012

Year	Cropping system
2007 – 2010	White clover (*Trifolium repens* L.) (WC) – Perennial ryegrass (*Lolium perenne* L.) ley
2010 – 2011	Organic winter wheat (*Triticum aestivum* L.) cv Clare, bi-cropped with black medic (*Medicago lupulina* L.) cv Virgo Pajbjerg (BM) and WC cv Aberpearl.
2011 – 2012	Organic spring wheat cv Paragon bi-cropped with BM and WC

Previous research on the site during 2010 - 2012 evaluated three contrasting cultivation techniques, including conventional plough-based tillage and two non-inversion tillage systems which differ on the degree of soil disturbance and residue incorporation (30% or >50% of residue cover) (Vijaya Bhaskar, 2014). Similar treatments were then used in the present study (See § 3.2.1).

3.1.1. Meteorological conditions

During the 2013 cropping season, the maximum and minimum air temperature was recorded in July of 19.0 °C and March of 3.1 °C while, the maximum and minimum rainfall documented was in March of 76.8 mm and July of 31.3 mm (Figure 3.1). The

2013 season experienced lower air temperatures compared with the long-term average. The 2013 spring period faced higher precipitations, particularly during March and May, while precipitations at summer time were lower compared to the seasonal average.

In the 2014 cropping season, the maximum and minimum air temperature were recorded in July of 18.0 °C and March of 7.17 °C, whereas the maximum and minimum rainfall documented were in May of 97.3 mm and March of 39.5 mm. 2014 experienced higher air temperatures across the season with higher precipitations during the spring period and lower precipitations recorded at summer time compared to long-time average (Figure 3.1).

The 2013 growing season experienced lower air temperature compared to the 2014 cropping season except during July and August when temperatures were higher in 2013 than in 2014 season. The 2013 season experienced lower precipitations compared with 2014 season except in March when precipitations were higher in 2013 (Figure 3.1).

Figure 3. 1. Mean precipitation and air temperature during 2013 and 2014 cropping seasons in comparison with the 10-year average. Royal Agricultural University meteorological station (NGR SP 42 004 011)
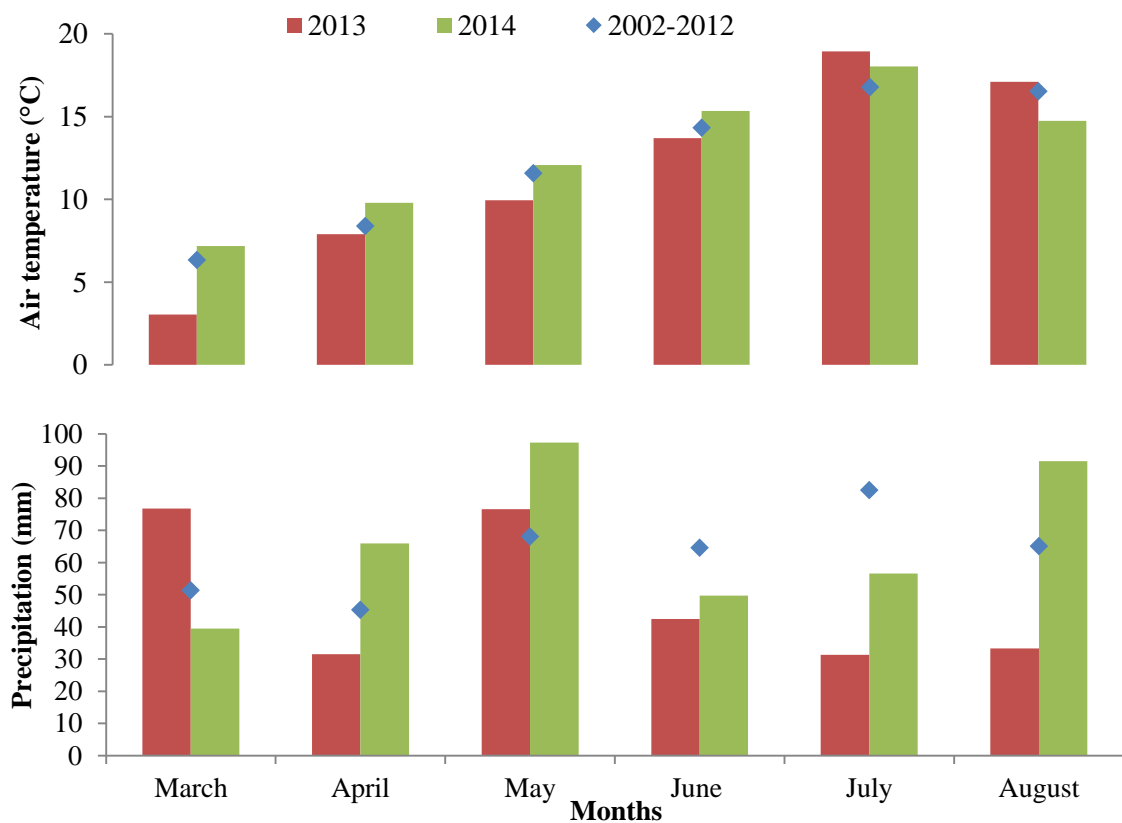
3.2. Experimental design and treatments

For both cropping seasons, field trials followed a split-split plot randomized block design. The selected field of 2.7 ha was divided into three separate blocks (90 m x 100 m). Each block was divided into three fully randomized main plots (cultivation treatments) of 30 m x 100 m. The main plots were divided into four fully randomized sub-plots (N treatments) (7.5 m x 100 m) and these were divided into three fully randomized split-sub plots (undersowing treatments) (30 m x 33.3 m) (Plate 3.2 & Figure 3.2). The treatment structure was as follows:

Spring wheat (3 block) x cultivation technique (9 main plot) x N fertilisation (36 sub plot) x undersowing (108 split-sub plot)

Plate 3. 2. Trial design after cultivation techniques, nitrogen application and undersowing treatments
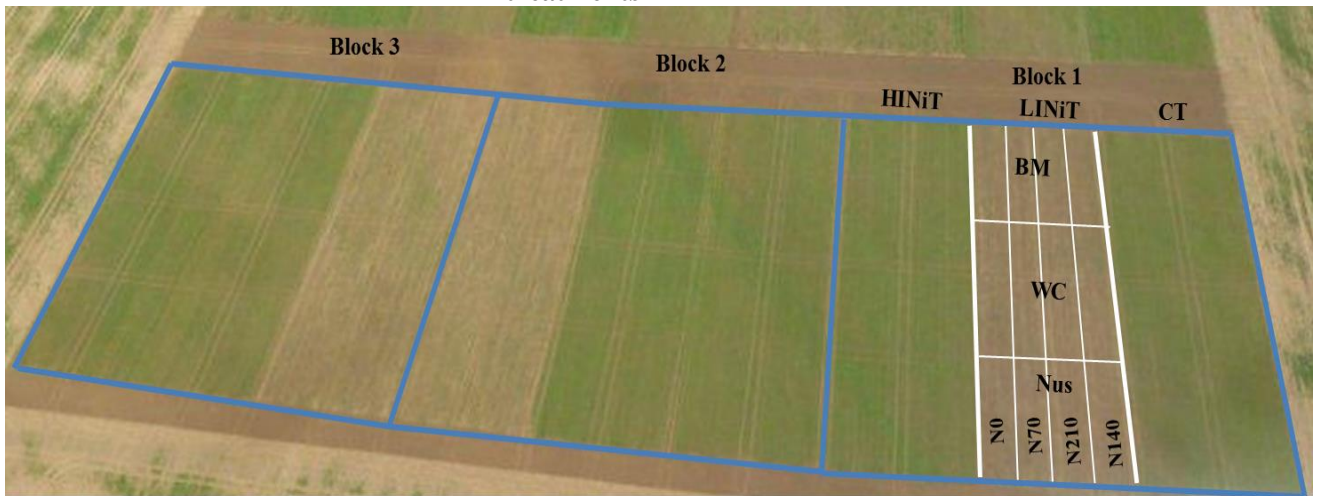
Figure 3. 2. Field trial design

CT; Conventional tillage

HINiT; High intensity non-inversion tillage

LINiT; Low intensity non-inversion tillage

N0; No fertiliser

N70; 70 kg N ha^{-1}

N140; 140 kg N ha^{-1}

N210; 210 kg N ha^{-1}

WC; white clover

BM; black medic

Nus; no undersowing
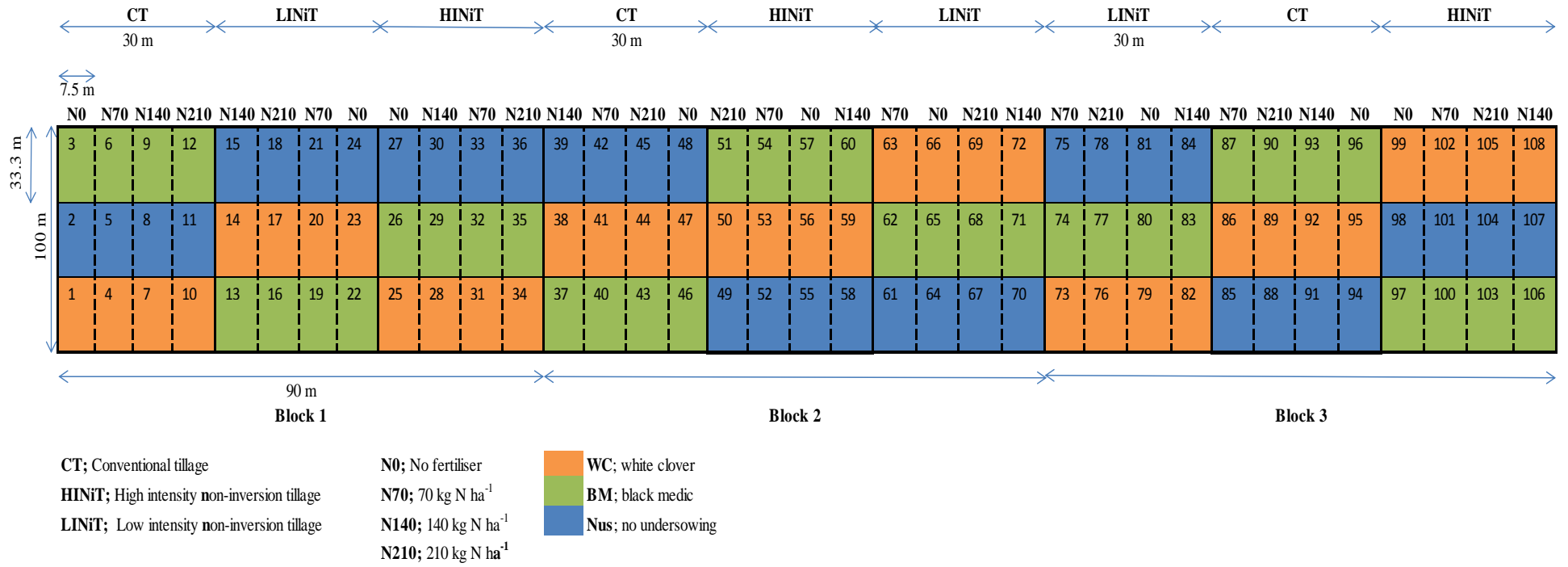
Before land preparation was initiated (20 March 2013 and 24 March 2014), foliar contact herbicide, glyphosate, was sprayed at 2 l ha^{-1}. Previous research on adjacent organic land reported considerable high weed pressure, particularly of grass weeds (Vijaya Bhaskar, 2014). Application of herbicide was made to reduce weed competition towards improving future crop yields.

The crop structure for both cropping seasons is detailed in Table 3.3.

Table 3. 3. Experimental wheat crop details	
Variety	Spring wheat cv Paragon
Sowing date	10 April 2013 / 18 April 2014
Seed rate	200 kg ha^{-1}
Thousand grain weigh	41.6 g
Seeds m^{-2}	480
Harvest date	27 August 2013 / 31 August 2014

Twenty days after sowing spring wheat in 2013, the experimental area was treated with triple superphosphate fertiliser (TSP) [Ca(H$_2$PO$_4$)$_2$H$_2$O] applied at a rate of 75 kg P$_2$O$_5$ ha^{-1}. Phosphate fertiliser was based on initial background level of soil P (Table 3.1) (DEFRA, 2010).

After 2013 harvest the field was left with surface residues over the winter and then 2014 core experiment was established.

3.2.1. Details of experimental treatments

3.2.1.1. Cultivation techniques

Three cultivation treatments (main plots) were examined in this study, two non-inversion tillage treatments and one conventional tillage treatment. More detailed information for each treatment is as follows:

- Conventional Tillage (CT); involved one pass of a five furrow Kverneland reversible plough, to a working depth of 20 cm, and then furrow pressed. Following, a Kuhn power harrow combination seed drill was used at a working depth of 8 cm (Plate 3.3). The percentage of soil cover by crop residues after drilling was typically assumed as 0% (Plate 3.4).

Plate 3. 3. Kuhn power harrow combination seed drill

Plate 3. 4. Seedbed conditions after contrasting cultivation systems

- High Intensity – Non-inversion Tillage (HINiT); consisted of two passes of a mounted Simba X-press with a Simba ST bar fitted ahead (Plate 3.5) at a working depth of 25 cm and 12 cm. A Vaderstad Rapid-A system disc in combination with seed drill (Plate 3.6) was employed to a working depth of 8 cm. The percentage of soil cover by crop residues after drilling was typically assumed as 30% (Plate 3.4).

Plate 3. 5. Simba Xpress with a Simba ST bar fitted ahead

Plate 3. 6. Vaderstad Rapid-A system disc combined with seed drill

- Low intensity – Non-inversion Tillage (LINiT); involved one pass of a mounted Simba X-press with a Simba ST bar fitted ahead at a working depth of 25 cm and 12 cm. A heavy planter Eco-dyn integrated seed drill followed at a working depth

of 26 cm to drill the crop (Plate 3.7). The percentage of soil cover by crop residues after drilling was typically assumed as >50% (Plate 3.4).

Plate 3. 7. Eco-dyn integrated seed drill

All the treatments had a uniform planting depth of 2 cm and coulter row spacing of 12.5 cm for 200 kg ha^{-1} volume of seeds. Crop residues were a mix of straw and herbicide-killed weeds and legumes from the previous cropping season (Plate 3.4).

<u>Varietal choice</u>

Spring wheat was selected due to increasing recognition of its high premium opportunities. In addition, unlike winter wheat, spring wheat has shorter growing season and present fewer tillers allowing studying more comprenhensively agricultural practice-induced effects on yield and yield components. The spring wheat variety was selected with particular attention to its potential bread-making quality and disease resistance. The oldest spring wheat in Group 1 (bread-making/milling) of the HGCA Recommended list – cv Paragon was selected, as it has a very good disease resistance and relatively long but stiff straw (HGCA, 2013). Paragon produces grains with very high protein content, and it has been reported to produce quality grain even under untreated trial conditions (NABIM, 2013).

Sowing date

Grain yield and other characteristics of wheat can be influenced by variations in sowing date (Hayward, 1990). Variable weather patterns across seasons can affect the selection of a suitable date for sowing. In the present study, the sowing date was adopted on the basis of pre-sowing cultivations and weather conditions, particularly prevailing precipitation.

Seed rate

Seeding rate can vary depending on sowing date, crop variety, soil type and weather conditions (Finch *et al*., 2014). Spring wheat varieties with lower production of tillers than winter wheat (Wibberley, 1984) should be complemented with high plant density to compensate towards securing a more optimum plant population. In this study, due to late sowing and in order to compare different cultivation techniques, a seeding rate of ≥ 400 seed m^{-2} was chosen.

Drilling depth

To ensure good seed distribution, drilling aims to be sufficiently deep enough. It can, however, be challenging to control due to its high dependency on seedbed preparation influenced by the contrasting pre-sowing cultivation techniques. A poor consolidated seedbed can, for example, result in deep seed placement while if the seedbed is too dense seeds may not be adequately covered resulting in losses due to pest damage (Atkinson, 2008). Additionally, the presence of residues in the non-inversion tillage systems may interfere with drills and generate both, an uneven sowing depth and seeding row spacing (Siemens *et al.,* 2004). Sowing depth recommendations for wheat are usually between 4 and 2 cm depth, depending upon soil type and conditions (HGCA, 2008b). For all the experiments, a uniform sowing depth of 2 cm and coulter row spacing of 12.5 cm were used for all the combination drills. Even though, the sowing depth and row space were kept almost uniform, the drills performance may vary depending on the pre-sowing cultivation techniques used.

3.2.1.2.Nitrogen treatments

Four mineral N fertiliser treatments (sub-plots) were used in the present study,

- N0 – No N fertilisation
- N70 – 70 kg N ha^{-1}
- N140 – 140 kg N ha^{-1}
- N210 – 210 kg N ha^{-1}

N fertiliser was applied as ammonium nitrate solution, NH_4NO_3 (34.5% N), sprayed using a 6 m width sprayer, Case IH GEM 3000sp (Plate 3.8). Tramlines were used as a form of traffic control. At all application rates, half of the treatments dose was applied at seedling growth and the remainder was applied at tillering stage. Further details are listed in Table 3.4.

Plate 3. 8. Fertiliser sprayer

Table 3. 4. Nitrogen treatments application dates with corresponding spring wheat growth stages (GS)

Year	Timing	Date	On/after GS
2013	1st	30 April	13
	2nd	23 May	21
2014	1st	10 May	13
	2nd	30 May	21

Nitrogen fertiliser type

Several studies have compared different types of inorganic N fertilisers, reporting no differences in yield response between fertilisers type (Christensen & Meintz, 1982; Garrido-Lestache *et al.,* 2004), suggesting that the amount of N applied and timing are more relevant, irrespectively of product type. Ammonium nitrate (NH_4NO_3) is one of the most common inorganic sources of N, containing 35% of N and with very rapidly available nitrate (Finch *et al*., 2014).

Nitrogen doses

Soil N supply (SNS) is defined as the soil mineral N (SMN) in soil plus the estimate of mineralisable N. The highest N dose used in this study, 210 kg N ha^{-1}, was selected following recommendations by DEFRA (2010), based on the SNS status assessed before the establishment of the field trial (February 2013). Subsequent treatments rates were based on 2/3 (140 kg N ha^{1}) and 1/3 (70 kg N ha^{1}) of the highest treatment dose respectively.

Timing and splitting of nitrogen applications

N fertiliser timing is one of the main factors influencing yields and grain quality (Borghi *et al*., 1997; López-Bellido *et al*., 1998). However, it has been argued in the case of spring wheat crops, for a most efficient utilization, N application timing is generally less critical due to the rapid crop growth and development (Gooding & Davies, 1997). Regardless of timing, splitting of N fertiliser doses have also been reported to potentially improve wheat N-use efficiency (López-Bellido *et al*., 2005; Mahler *et al*., 1994) although, the proportions of the split should be determined based on initial soil fertility status. In the present study, N applications were split by half, being applied at the seedling stage (on/or after GS13) and at tillering (on/or after GS21). Splitting applications were based on recommendations for the higheest doses, N210 and N140 (DEFRA, 2010), whereas the lowest dose (N70) was split in order to maintain the same conditions for all applications.

3.2.1.3.Undersowing

For the undersowing treatments (split-sub plot), two legumes species were compared, white clover (*Trifolium repens*) cv Aberpearl at 7 kg ha^{-1} (WC) and black medic (*Medicago lupulina*) cv Virgo Pajbjerg sown at 8 kg ha^{-1} (BM). Legumes were hand broadcasted into the established spring wheat stand or not undersown (Nus), on 7 May 2013 and 12 May 2014, on/or after GS13.

Undersown legume species choice

Legumes species were selected based on their ability to grow into the emerged crop; their ability to compete against weeds, and potentially less aggressive competition towards the main crop (Döring *et al*., 2013; Rosenfeld *et al*., 2011; Vijaya Bhaskar *et al*., 2013c).

White clover (WC) is a perennial legume with a slow establishment but considerable production of biomass (Döring *et al*., 2013) which made it particularly suitable for undersowing, and it also offers good weed control (Rosenfeld *et al*., 2011). WC ability to fix atmospheric N results in a widely variable contribution of N which is estimated of about 250 kg ha^{-1} of N per year (Smýkal *et al*., 2015). This legume species also exhibits great winter hardiness and persistence, attributable to the formation of a complex network of stolons (Jones, 1992; Smýkal *et al*., 2015). A great number of WC varieties have been developed as a result of a large number of breading programs (Döring *et al*., 2013) and grouped into small, medium and large leaved types (Rosenfeld *et al*., 2011). WC cv Aberpearl is a small leaved variety, best suitable for undersowing due to less aggressive growth against the main wheat crop.

Black medic (BM) is a short-lived annual/biannual specie (Clapham *et al*., 1987) slow to establish, but with a fast develop (Hartmann *et al*., 2009) and great biomass production allowing good weed suppression (Döring *et al*., 2013). BM cv Pajbjerg is the only variety currently use in the UK (Rosenfeld *et al*., 2011).

3.3.Aboveground assessments

3.3.1. Developmental stages

For all sampling assessments, growth stages (GS) were based on the decimal code devised by Zadoks *et al*., (1974). Date of maturity was judged when grain moisture content had reached 15%. Details of dates and developmental stage for each plant assessment are given in Table 3.5.

Table 3. 5. Dates and growth stages for above ground crop assessment

Assessments	Approximate wheat growth stage
Wheat establishment and tillers number	On/or before GS31
Wheat shoot numbers	On/or after GS31
Growth assessments (wheat, weeds & legumes – BM & WC – biomass)	On/or before GS31; on/or after GS61; on/or after GS71
Plant height	On/or after GS71
Wheat ears number	On/or after GS71
Diseases assessment	On/or after GS71
Biological harvest	On/or after GS87

3.3.2. Assessments

Plant establishment

Plant establishment was determined by counting the number of plants inside a 0.25 m^2 random quadrat for each split-sub plot with ten replications. The assessments were performed twice a week following drilling to monitor the emergence of the crop, and were continued until no further plants emerged.

Tillers number and shoots number

Wheat tillers number and total wheat shoot number (main stem and tillers) were assessed using a 0.25 m^2 random quadrat with ten replications per each split-sub plot.

Growth assessments

In 2013 two destructive harvests were assessed by growth analyses, while in 2014 three destructive harvests were sampled. Samples of all the aboveground plant material were collected from random areas in order to avoid bias. Sampling was conducted with three replications and avoiding the previously disturbed area. All the aboveground plant material inside a 0.25 m^2 random quadrat was recovered using scissors or secateurs. All cut material was place as quickly as possible inside labelled plastic bags and sealed. In the laboratory, wheat, legumes (WC & BM) and weed species were separated and fresh weights recorded. Dry weight (DM) yield was recorded after drying samples at 105°C overnight.

The non-undersowing (Nus) treatment was not completely free of legumes due to some small natural regeneration, by stolons (WC) and adventitious bud in roots (BM), in spite of pre-cultivation herbicide applications. Legumes were, therefore, separated from weed even though they were considered legumes weeds in these plots rather than deliberately undersown legumes.

Plant height and wheat ears number

Height of the main wheat shoot was measured from the tip of the ear to the nearest centimetre from the ground level, at fifteen randomly selected fertile shoots per split-sub plot. Measurements were taken using a rising disk apparatus, a rectangular (30 x 50 cm) expanded polystyrene weighing 50 g with a hole centrally bored (4 cm diameter) into which a graduated wooden rod was inserted. The scale was positioned so that the top of the disc recorded zero when the base of the disc was at soil level.

The number of wheat ears was assessed using a 0.25 m^2 random quadrat with ten replications per each split-sub plot.

Disease assessment

The incidence of septoria leaf blotch of wheat (*Zymoseptoria tritici* Desm. Quaedvlieg & Crous), and leaf rust of wheat (*Puccinia triticina* Erikss.) severity percentages were evaluated on 10 flag leaf samples per each split-sub plot, using an illustrated key (James, 1971). Take-all (*Gaeumannomyces graminis* var *tritici*) severity percentages

was evaluated in 10 plants per each split-sub plot, using an illustrated key (MAFF, 1976). Illustrated keys are given in Appendix 1.

Final biological harvest

The trial was hand harvested following the same protocol used for growth assessments, using 0.25 m^2 random quadrats, with three replications at each split-sub plot. All the plant material was separated into wheat (separated by ears and straw), legumes (BM & WC) and weeds, and their fresh weight assessed. Ears were cut off at the peduncle and number recorded. All samples were dried at 105°C overnight and DM recorded. Ears were threshed by hand and the amount of grain was weighed to obtain total grain weights and grain yield, which was corrected to 15% grain moisture content. Thousand grain weight (TGW) was recorded after using an automatic feeder and counter (Farm-tec, Scunthorpe). Harvest index (HI) was determined as the ratio of grain weights to the total wheat aboveground biomass (Donald & Hambling, 1976).

Plant nitrogen content

In order to determine the N content, all the plant samples were course milled and then sub sampled and further micro-milled (0.5 mm sieve) (Cyclotec 1093 Sample Mill) to obtain a fine sample with a narrow particle size distribution. A sub sample of 25 mg (± 0.05 mg) of the ground material plus 50 mg of tungsten oxide were placed into aluminium foils and weighed on a five place analytical balance. Encapsulated samples were then analysed on an Elemental Cube CNS auto analyser (Elementar Analysen systemse GmbH). Grain protein content was obtained by multiplying grain N% by 5.7 (Osborne, 1907). Total grain N uptake, total wheat N uptake (total grain N uptake plus total straw N uptake), total legume and weeds N uptake, and the N harvest index were calculated using the following formulas (Fageria $et\ al.$, 2008; Moll $et\ al.$, 1982),

$$\text{Total grain N uptake (kg ha}^{-1}) = \left(\frac{\text{Grain yield (t ha}^{-1})}{100} \times \text{grain N\%} \right) \times 1000$$

$$\text{Total plant N uptake (kg ha}^{-1}) = \left(\frac{\text{DM (t ha}^{-1})}{100} \times \text{N\%} \right) \times 1000$$

$$\text{Nitrogen harvest index (\%)} = \left(\frac{\text{N\% in grains}}{\text{N\% in grains} + \text{N\% in straw}} \right) \times 100$$

Nitrogen-use efficiency parameters

The following N-efficiency parameters were calculated for each treatment:

-   N-use efficiency (NUE; kg kg^{-1}) as the ratio of grain yield to N supply.
-   N uptake efficiency (NUpE; kg kg^{-1}) as the ratio of total aboveground plant N uptake to N supply.
-   N utilisation efficiency (NUtE; kg kg^{-1}) as the ratio of grain yield to total aboveground plant N uptake.
-   N harvest index (NHI; %) as the ratio of grain N uptake to total aboveground plant N uptake.

The amount of N supply is the sum of SMN (ammonium plus nitrate) at sowing, mineralised N and N fertiliser applied. Mineralised N was estimated as the total plant N uptake at harvest plus mineral N left in soil profile after wheat harvest in control plots (N0) minus initial mineral N presented before wheat seeding (Huggins & Pan, 1993; Miao *et al*., 2015). N in the roots was not considered in the calculations, due to practical experimental difficulties and sometimes low biomass. The terminology for N efficiency parameters follows Delogu *et al*. (1998), Huggins & Pan (1993), López-Bellido *et al*. (2005); Moll *et al*. (1982), Pierce & Rice (1988) and Sowers *et al*. (1994).

3.4. Soil assessments

3.4.1. Soil chemical analysis

Field sampling

Soils were sampled to a depth of 25 cm at fifteen randomly points following a W pattern within each split-sub plot using a Dutch auger. Samples were hand-crumbled

and hand-mixed to form representative samples. Samples were placed in sealed and labelled bags, and rapidly transferred to the laboratory. Initial processing and analyses occurred within 12 hours of sampling. The following analyses were then conducted:

Soil mineral nitrogen

Soil available mineral N (ammonium and nitrate) (SMN) was determined by a potassium sulphate (K_2SO_4) extraction method (Faithfull, 2002). Soils were sampled to a 25 cm depth, following the field sampling procedure previously described. Assessments were initiated from March (2013 and 2014) and continued throughout the cropping seasons at 4-week intervals and finished in August 2013 and 2014. Analyses were conducted on the same day of sampling.

In the laboratory, samples were passed through a 6.7 mm mesh sieve and any plant material or visible stone were removed. From each sample, three analytical replications of 25 g (± 0.02 g) were taken and transferred onto a labelled extraction bottle adding 100 ml of 0.5 M K_2SO_4 solution. In each extraction batch, 2 blanks were included. The extraction bottles were shaken vigorously using a shaker unit (Gerhardt, Germany) for 30 mins and allowed to stand for 15 min. The soil solutions were then filtered through Whatman No 40 filter papers onto a 60 ml labelled sample bottles, discarding the first couple of drops. Samples bottles containing the collected extracts were store frozen in preparation for analysis of NH_4 and NO_3 on a FiAstar^{TM} 5000 Analyser (DK) based on flow injection analysis and colorimetric methods.

To convert SMN (mg l^{-1}) to an area basis (kg ha^{-1}), the soil bulk density is required and calculated as Unkovick et $al.$ (2008),

$$SMN\left(\frac{mg}{kg}\right) = \frac{\frac{\text{extraction volume (ml) x total extract mineral N } (NO_3^-, NH_4^+)(\frac{ml}{l})}{1000}}{\frac{\text{Soil dry weight (g)}}{1000}}$$

$$SMN\left(\frac{kg\ N}{ha}\right) = SMN\left(\frac{mg}{kg}\right) \text{ x bulk density x depth factor}$$

Soil moisture content

Soil dry matter was assessed by weighing 50 g (± 0.05 g) of fresh soil samples from each split-sub plot and oven dried at 105°C overnight and the weights retaken. The soil moisture (gravimetric) percentage was obtained using the following formula (Brady & Weil, 1999),

$$\text{Soil gravimetric moisture(\%)} = \frac{\text{soil fresh weight - soil dry weight}}{\text{Soil dry weight}} \times 100$$

Assessments were initiated from March (2013 and 2014) and continued throughout the cropping seasons at 4-week intervals and finished in August 2013 and 2014.

Soil pH

Determination of soil pH was conducted by weighing three analytical replicas (per sample) of 20 g of sieved (≤2 mm) air-dry soil into shaking bottles and adding 50 ml of deionised water and shaken vigorously for 15 min, using a shaker unit (Gerhardt, Germany) and allowed to stand. A pH electrode was immersed in the solution, swirling a couple of times allowing the pH to stabilize before taking readings (Faithfull, 2002). Before pH measurements, calibration of the pH meter (Omega Engineering, USA) was performed according to manufacturer's instructions using buffers of pH 7.0 and 4.0 to cover the pH range of the soil samples.

Soil potassium and magnesium

Soil potassium (K) and magnesium (Mg) were assessed before the establishment of the experimental study (March 2013). K and Mg were determined by ammonium nitrate extraction (Faithfull, 2002). From each split-sub plot, three analytical samples of 10 g (± 0.05 g) of sieved (≤2 mm) air-dry soil was transferred into a 150 ml shaking bottles and 50 ml of N ammonium nitrate dispensed. Bottles were shaken vigorously using a shaker unit (Gerhardt, Germany) for 30 mins and allowed to stand for 15 mins. Solutions were subsequently filtered through Whatman No 2 filter papers, discarding the first couple of drops. The concentration of K in the extraction samples and in six working standards (0, 1, 2, 3, 4 and 5 µg K ml^{-1}) and two blanks, were determined using a flame photometer.

From the standard graph, the µg K ml^{-1} equivalent in the samples were determined and blank value subtracted and difference multiplied by five (initial extraction ratio), resulting in the number of mg l^{-1} extractable K in the air-dry soil samples.

To determine Mg concentration, sub-samples of the ammonium nitrate extraction were used. From the extracted solutions, 5 ml was pipetted into a 100 ml volumetric flask adding 1 ml buffer and diluted to 100 ml's with deionised water. The concentration of Mg in the solutions and in six working standards (0, 0.2, 0.4, 0.6, 0.8 and 1 µg Mg ml^{-1}) and two blanks were determined by using an atomic absorption spectrophotometer (Thermo Scientific Inc., USA).

Soil phosphorus

Soil phosphorus (P) content was measured before the establishment of the experimental study (March 2013) by the Olsen Method (Olsen *et al*., 1954). From each split-sub plot, three analytical samples of 5 g (± 0.05 g) of sieved (≤2 mm) air-dry soil were weighed and transferred into 150 ml shaking bottles. A teaspoon of powdered charcoal and 100 ml of sodium bicarbonate (NaHCO$_3$) reagent, at pH 8.5, were added to the bottles and then shaken vigorously using a shaker unit (Gerhardt, Germany) for 30 mins and allowed to stand for 15 mins. Solutions were filtered through Whatman No 2 filter papers, discarding the first few drops of filtrate. From the extractions, 5 ml was pipetted into a 100 ml conical flask slowly adding 1 ml of 1.5 M sulphuric acid. When frothing ceased from releasing carbon dioxide, 20 ml of ammonium molybdate (1.2% m/v)/ascorbic acid solution was added and allowed to stand for 30 mins. Working standard solutions of 0.25, 0.5, 1, 2, 3, 4, 5 and 6 µg P ml^{-1} were used in order to obtain the equivalent µg P ml^{-1} of the samples and 2 blanks were used. Finally, the absorbance of the samples, standards and blanks were measured using a spectrophotometer (Cecil Instruments Lt., UK) at 880 nm wave-lengths. P was assessed before the establishment of the experimental study (March 2013).

3.4.2. Soil physical analysis

Soil texture

Soil texture was determined following the Bouyoucos Hydrometer Method (Bouyoucos, 1962) before the establishment of the experimental study (March 2013). From each main plot, three analytical samples of 50 g (± 0.01 g) of sieved (≤2 mm) air-dry soil were placed into 250 ml shaking bottles. 100 ml of Calgon solution was added and shaken for 400 mins. The solutions were transferred into a 1000 ml cylinder and diluted to 1000 ml's using deionised water. The top of the cylinder were sealed with parafilm and inverted 20 times; placed on the bench and timed immediately with a stop watch. A hydrometer was inserted into each cylinder without disturbing the solution approximately 20 sec prior to a reading being taken; then removed and rinsed immediately. Readings were taken at 40 secs, 4 mins, 37 mins and 2 hours. Readings gave the density in g l^{-1}. To correct the readings for temperature and density, readings were calibrated against the hydrometer in the Calgon-water control solution and subtracted from all the readings. The percentage of sand, silt and clay fractions was plotted on the triangular texture chart to determine texture class (MAFF, 1988).

Soil bulk density

Soil bulk density was determined following the ISO 11272:1998 method (ISO 11272:2014) for non-gravely soils. Bulk density was only measured before the cultivations treatments preformance (2013), in order to obtain initial values. Soil samples were taken from each main plot with three replications at a depth of 30 cm with 5 cm intervals. Bulk density was determined on undisturbed soil samples using a steel sampler cylinder of 358.36 cm^3 which was driven perpendicular, without deflection and compaction, into the soil surface. Samplers were removed carefully in order to prevent any loss of soil. Using a flat-bladed knife, the excess of soil from the sample holder was removed leaving the bottom of the sample holder flat and even with edges of the holder. Samplers were placed in a labelled plastic bag and sealed. In the laboratory the weight of the soil samples at a 5 cm interval were recorded to calculate soil water content. Samples were placed in an oven at 105°C until constant mass was reached (minimum 48 hours) and then the dry weight was recorded. Using the oven dry weight and the

volume of the sample holder, the soil bulk density was calculated using the following formula,

$$\text{Soil bulk density (g cm}^{-3}) = \frac{\text{Soil dry mass (g)}}{\text{Volume of the sample (cm}^{-3})}$$

Soil bulk density value was then used to convert SMN (mg l^{-1}) to an area basis (kg ha^{-1}), see § 3.4.1.Soil chemical analysis - soil mineral nitrogen.

Soil penetration resistance

Soil penetration resistance was measured at 5, 10, 15 and 30 cm soil depth using a hand cone penetrometer with base area of 3.33 cm^2, 60° included angle and 80 cm driving shaft (Model 06.01.SA, Eijkelkamp Agrisearch Equipment, The Netherlands), following standard procedures (ASAE, 1994). Assessments were performed at 10 random positions from each main plot before and after cultivations, and harvest. The device was pushed perpendicular into the soil and the resistance (in N, Newton) and appropriate depth were recorded. The cone resistance was estimated by the ratio of the manometer reading (N) to the base area (cm^2) and then transformed to mega Pascal (MPa) units.

3.5.Statistical analysis

All the data collected were analysed using the split-split plot analysis of variance (ANOVA) model in Genstat (15th Edition VSN International Ltd, Hemel Hempstead, UK). Uniformity and residuals of all the data sets were verified before reporting results. The ANOVA results are reported quoting treatment means, residual degrees of freedom (df), standard error of difference (SED) or Fisher's Protected Least Significant Differences (LSD) and the *P*-value at significant level of *P*<0.05. When necessary, correlation and regression analyses were also applied.

CHAPTER FOUR

Core experiment I – spring wheat 2013

4.1.Introduction

Cultivation techniques significantly influence the soil environment affecting crop germination, growth and development (Arvidsson *et al*., 2013; Gajri *et al*, 2002; Morris *et al*., 2010; Silgram & Sheperd, 1999). In a clay soil, the use of plough and power harrows in conventional tillage (CT) can break the soil structure and clods, while mixing and incorporating plant residues creating a smooth and level soil surface (Bell, 1996; Soffe, 2003). Increasing soil movement can also intensify organic matter mineralisation, increasing N availability for the crop after cultivation operations (Silgram & Shepherd, 1999; Wild, 1988). However, continued use of CT operations reportedly leads to negative effects (see Table 2.1), as reported by others (e.g. Mitchell *et al.,* 2004; Six *et al*., 2000)

In order to reduce potential negative effects by CT, non-inversion tillage has been widely used and increasingly adopted (Cannell & Hawes, 1994; Holland 2004; Jones *et al.,* 2006). These tillage systems create a seedbed using discs and tines without soil inversion, leaving a substantial part of the plant residues on the soil surface and/or mixed within topsoil layers (Soffe, 2003). Non-inversion tillage systems also reportedly increase organic matter in the very surface layer (Carter, 1991) and can reduce costs (Morris *et al*., 2010; Soane *et al*., 2012). However, detrimental effects of non-inversion tillage can sometimes result in lower crop yield compared with CT (see Table 2.4), as reported by several studies (López-Bellido *et al*., 1998; Vijaya Bhaskar *et al*., 2013b).

Mineral N application effects on crop production have been widely studied due to its influences on crop growth and development (Cossani *et al*., 2009; López-Bellido, *et al*., 1998; Otteson *et al*., 2008) (see Table 2.5). For grain production, N fertilisation often increases yield when increasing N rates until this response is reduced with over-supply, while grain protein generally gives a linear response to N increases in various growing environments (López-Bellido *et al*., 1998; López-Bellido *et al*., 2001). However, several authors reported that weather conditions play an important role in highlighting

negative or positive effects of N fertilisation supply on grain protein and its negative correlation with grain yield (Campbell *et al*., 1977; Smith & Gooding, 1999; Terman *et al*., 1996). N fertilisation can also potentially benefit weeds, which then compete for resources with the crop (Di Tomaso, 1995; Moss *et al*., 2004; Sheibani & Ghadiri, 2012). Although, it can also indirectly control weed pressure by encouraging crop growth biomass and increasing crop competitiveness (Grundy *et al.,* 1993; Jørnsgård *et al*., 1996).

Legumes intercropped in UK are commonly utilised in the form of undersowing. Undersowing legume into the wheat crop stand in spring (Hartl, 1989) can potentially reduce competition between undersown and main crops (Charles, 1958). Undersowing covers the ground after the main crop harvest, allowing understorey species to possibly reduce weed presence by competing for resources (Liebman & Dyck, 1993; Thiessen-Martens *et al*., 2001). Additionally, undersowing can suppress pests and diseases (Hiltbrunner *et al*., 2002) but such effects depend on the undersown species, sowing time, harvest management and environmental conditions (Hartwig & Ammon, 2002). Using undersowing species with vigorous growth can potentially control weeds without negatively affecting the main crop and allowing sometimes greater final yields (Brennan & Smith, 2005; Haymes & Lee, 1994; Hauggaard-Nielsen *et al*., 2008).

A field experiment was established in order to evaluate the effect of contrasting cultivation techniques, increasing mineral N fertilisation rates and undersowing legumes on growth, development and final yield of spring wheat.

4.2.Material and methods

4.2.1. Experimental site

The field experiment was performed at the Royal Agricultural University's Harnhill' Manor Farm, Cirencester, UK (NGR SP 075 006). The area was previously managed by either conventional tillage or by two inversion tillage systems distinguished by soil movement intensity and soil surface coverage (30% or >30%) (Vijaya Bhaskar, 2014).

S*inapsis alba* cv Tilney was subsequently broadcasted in order to control take-all disease (*Gaeumannomyces graminis* var *tritici*) incidence in the field (HGCA, 2006).

4.2.2. Experimental design and treatment structure

The study was conducted from March 2013 to August 2013 on a field previously cropped with organic spring wheat cv Paragon. The experimental design and treatment structure were previously described in Chapter 3, Material and Methods, § 3.1. Before cultivation techniques operations in March 2013, 2 l ha^{-1} of non-selective contact herbicide, a.i. glyphosate (Round-up) was applied across the entire experimental site. The 2013 dates for each field operation are reported in Table 4.1.

Table 4. 1. Diary of 2013 field operations

Field operation	Approximate date
Herbicide application	03 March 2013
Land preparation	20 March 2013
Spring wheat sowing	10 April 2013
Nitrogen applications	30 April / 23 May 2013
Undersowing	7 May 2013
Harvest	27 August 2013

4.2.3. Meteorological conditions

During the 2013 cropping season, maximum of 18.95°C was recorded in July while minimum temperature of 3.05 °C was recorded in March. Maximum and minimum rainfall documented were 76.8 mm in March and 31.3 mm in July. The 2013 growing season experienced lower air temperatures compared with the long-term average. The spring experienced higher precipitations, particularly in March and May, while rainfall in summer time was much lower, compared with the long-time average (Figure 4.1).

Figure 4. 1. Mean air temperatures and precipitation during the 2013 experimental period in comparison with the 10-year average. Royal Agricultural University meteorological station (NGR SP 42 004 011)

	March	April	May	June	July	August
■ 2013	3.05	7.90	9.95	13.70	18.95	17.10
◆ 2002-2012	7.48	10.28	13.05	16.34	18.27	18.43

Air temperature (°C)

	March	April	May	June	July	August
■ 2013	76.80	31.50	76.60	42.50	31.30	33.30
◆ 2002-2012	51.39	45.37	68.15	64.60	82.57	65.15

Precipitation (mm)
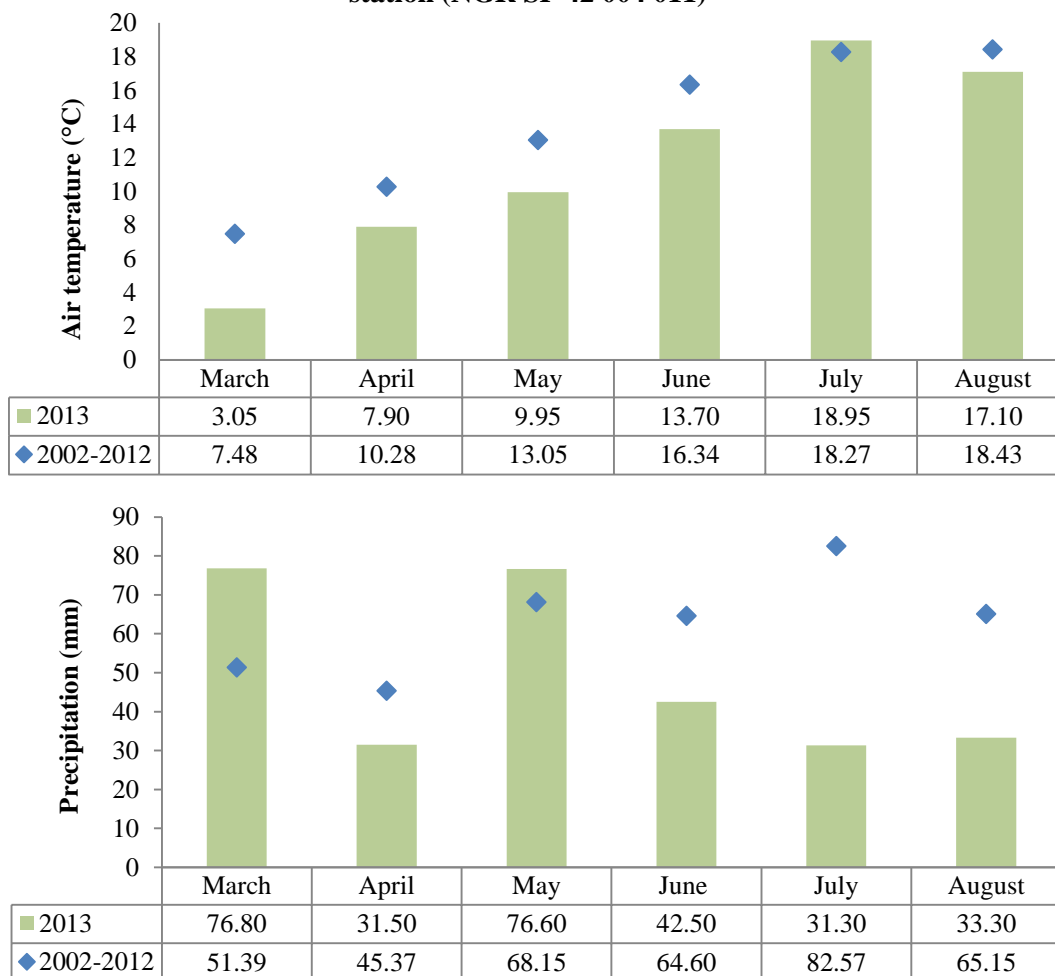
4.2.4. Assessments

4.2.4.1. Above ground assessments

Above ground assessment were previously described in Chapter 3, Material and Methods, § 3.3. Further details are presented in Table 4.2.

Table 4. 2. Above ground assessments dates for spring wheat 2013

Assessments	Approximate date
Wheat establishment	17 May 2013
Wheat tiller number	20 May 2013
Wheat shoot numbers	10 June 2013
Growth assessments (wheat, weeds and legumes –	24 May 2013
BM and WC – biomass)	01 July 2013
Plant height	26 July 2013
Wheat ears number	27 July 2013
Diseases assessment	29 July 2013
Biological harvest	27 August 2013

4.2.4.2.Soil assessments

Soil assessments were previously described in Chapter 3, Material and Methods, § 3.4. Further details are given in Table 4.3.

Table 4. 3. Soil assessment dates for spring wheat 2013

Assessments	Approximate date
Soil mineral nitrogen, moisture (gravimetric) content	Monthly. March 2013 – August 2013
Soil pH	20 April, 10 June, 15 August 2013
Soil penetration resistance	29 February, 20 April, 10 June, 15 August 2013

4.2.5. Statistical analysis

Statistical analysis and reporting results were previously described in Chapter 3, Material and Methods, §3.5. The severity of diseases was transformed using log-normal transformation ($\log(x!)$) ($x + 1$; x= percentage of leaf infected) in Genstat (15th Edition VSN International Ltd, Hemel Hempstead, UK), to reduce heterogeneity of variance.

4.3. Results

4.3.1. Establishment

There was a significant cultivation techniques effect on wheat establishment ($P<0.001$) with an overall mean establishment of 77%. CT resulted in greater plant establishment (96%) than HINiT (85%), followed by LINiT (53%) (Table 4.4). N fertilisation and undersowing treatments did not show significant effects on crop establishment.

Table 4. 4. Effect of cultivation techniques and nitrogen fertilisation on spring wheat establishment

	Establishment (number m^{-2})
CT	461.10c
HINiT	406.30b
LINiT	252.40a
SED (4 df)	*10.86*
P	***
N0	356.50a
N70	365.60a
N140	378.90a
N210	392.00a
SED (18 df)	*18.44*
P	*ns*

Values followed by same letter, do not differ significantly at $P<0.05$. ***= $P<0.001$, *ns*= no significant

Due to interactions, LINiT resulted in significant higher ($P<0.05$) crop establishment when N210 was applied (Figure 4.2). CT resulted in greater establishment than LINiT in spite of the N dose applied, while differences between CT and HINiT were only significant with N140 application.

Figure 4. 2. Effect of cultivation techniques and nitrogen fertilisation interaction on spring wheat establishment
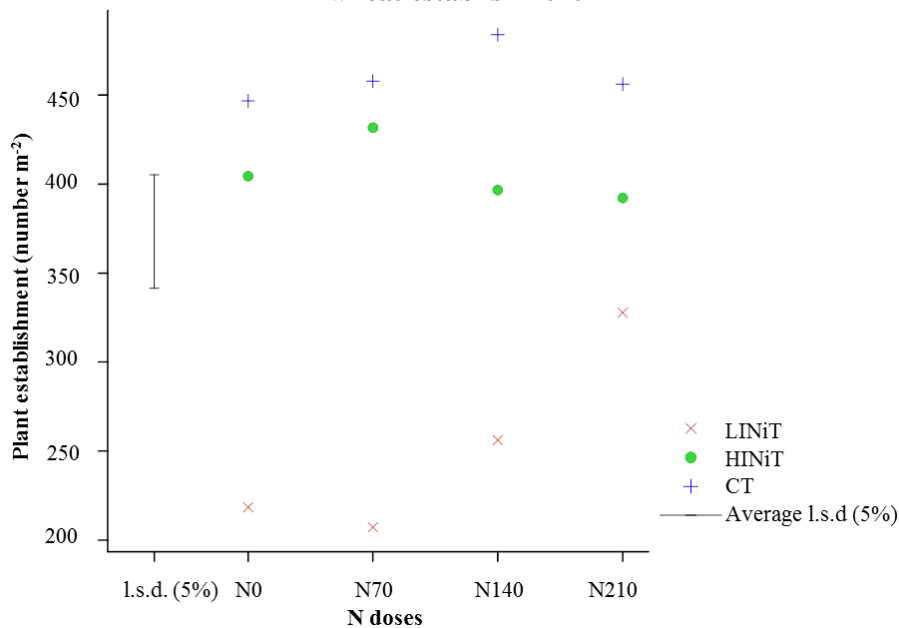
Error bars representing average LSD (*P*<0.05)

4.3.2. Tillers and total shoot production

Tillers production and total shoot number were significantly affected (*P*<0.01) by cultivation techniques and N fertilisation treatments. A higher numbers of tillers were produced under CT and HINiT compared with LINiT, while the highest total shoots number was under CT (Table 4.5). Increases in N rate significantly increased (*P*<0.01) tillers and total shoots number, with the higher tillers and shoots number with N210, compared specifically with the unfertilised treatment. There was no significant effect of undersowing on tillers and total shoot production.

Additionally, the production of total shoots was significantly affected (*P*<0.01) by cultivation techniques and N fertilisation interaction, provinding greater production under CT with 140 kg N ha^{-1} was applied (Figure 4.3). On the other hand, HINiT resulted in greater shoot number when either N70 or N210 were applied, while LINiT only increased shoots number with N210 (Figure 4.3).

Table 4. 5. Effect of cultivation techniques and nitrogen fertilisation on spring wheat tillers and total shoots production

	Tillers (number m^{-2})	Total shoot (number m^{-2})
CT	1103.60b	895.60c
HINiT	961.70b	674.80b
LINiT	630.00a	612.50a
SED (4 df)	*69.7*	*17.1*
P	**	***
N0	721.60a	625.00a
N70	875.60ab	703.10ab
N140	932.70bc	753.00bc
N210	1063.90c	829.40c
SED (18 df)	*79.7*	*44.8*
P	**	**

Values followed by same letter, do not differ significantly at *P<0.05*. **= *P<0.01*, and ***=*P<0.001*

Figure 4. 3. Effect of cultivation techniques and nitrogen fertilisation interaction on spring wheat total shoots production

Error bars representing average LSD (*P<0.05*)
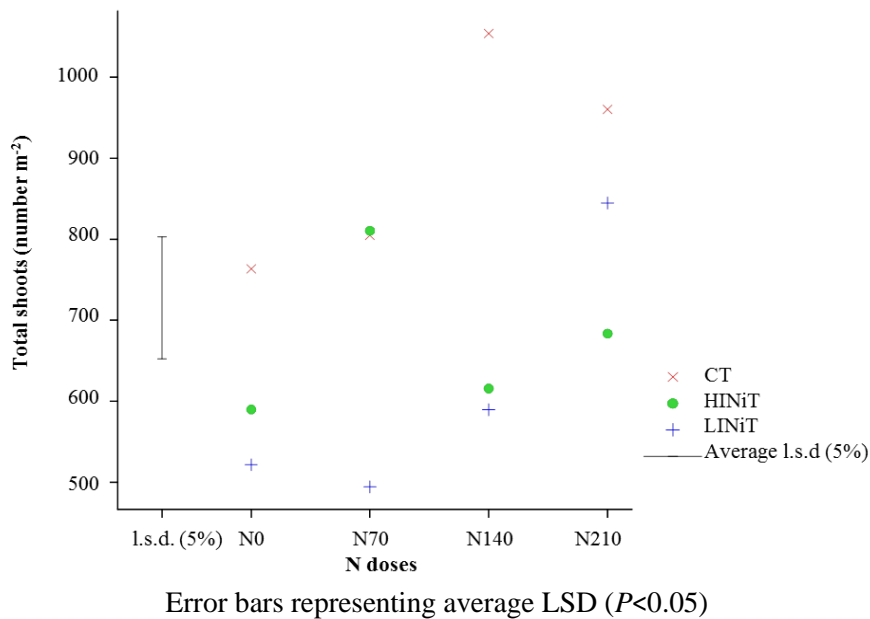
4.3.3. Mid-season wheat biomass and nitrogen uptake

<u>May assessment</u>

During May assessment, CT and HINiT produced a significantly greater wheat DM ($P<0.001$) and total wheat N uptake ($P<0.01$) than LINiT (Table 4.6). N fertilisation significantly increased wheat biomass production ($P<0.05$) and total wheat N uptake ($P<0.01$), compared with unfertilised treatment.

Table 4. 6. Effect of cultivation techniques and nitrogen fertilisation on spring wheat biomass and N uptake (May 2013)

	Wheat DM (t ha^{-1}) May	Total wheat N uptake (kg N ha^{-1}) May
CT	0.502b	20.53b
HINiT	0.456b	18.65b
LINiT	0.186a	8.83a
SED (4 df)	*0.034*	*1.51*
P	***	**
N0	0.341a	13.09a
N70	0.389b	15.87b
N140	0.389b	17.02b
N210	0.407b	18.03b
SED (18 df)	*0.023*	*1.08*
P	*	**

Values followed by same letter, do not differ significantly at *P<0.05*. *= P<0.05*; ***= P<0.01*; ***= P<0.001*, and *ns*= no significant

Due to significant interactions ($P<0.05$), LINiT resulted in a greater wheat DM with 210 kg N ha^{-1}, compared specifically with N70 and N0 (Figure 4.4). CT and HINiT produced higher wheat biomass compared with LINiT, with up to 140 kg N ha^{-1}. However, under N210, CT resulted in higher wheat DM than HINiT, and then LINiT.

Figure 4. 4. Effect of cultivation techniques and nitrogen fertilisation interaction on spring wheat biomass (May 2013)
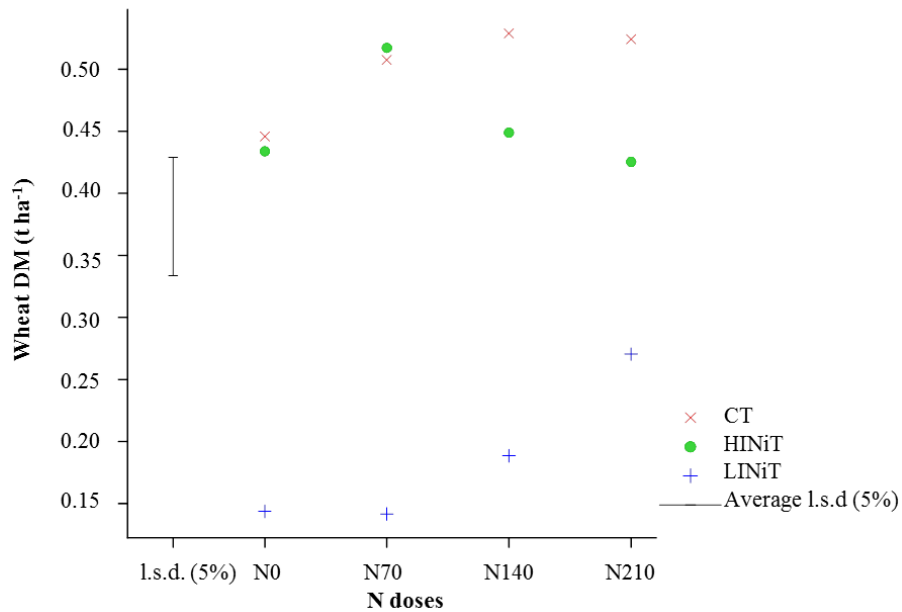
Error bars representing average LSD (*P*<0.05)

A significant interaction between cultivation techniques and N fertilisation treatments was also observed on wheat N uptake (Figure 4.5). LINiT resulted in greater wheat N uptake when N210 was applied, compared specifically with N70 and N0. CT increased N uptake when either N140 or N210 were applied than specifically with N0. However, no significant effect was found between N rates under HINiT.

Figure 4. 5. Effect of cultivation techniques and nitrogen fertilisation interaction on spring wheat N uptake (May 2013)

Error bars representing average LSD (*P*<0.05)
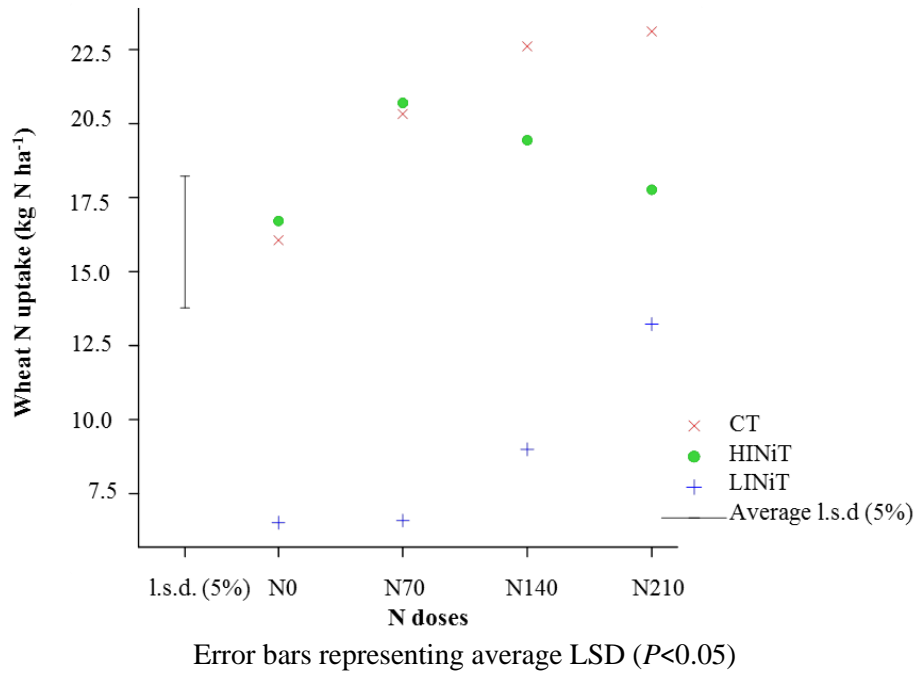
Additionally, due to significant interaction, LINiT resulted in lower N uptake than CT and HINiT, regardless of the undersowing treatment (Figure 4.6).

Figure 4. 6. Effect of cultivation techniques and undersowing interaction on spring wheat N uptake (May 2013)

Error bars representing average LSD (*P*<0.05)
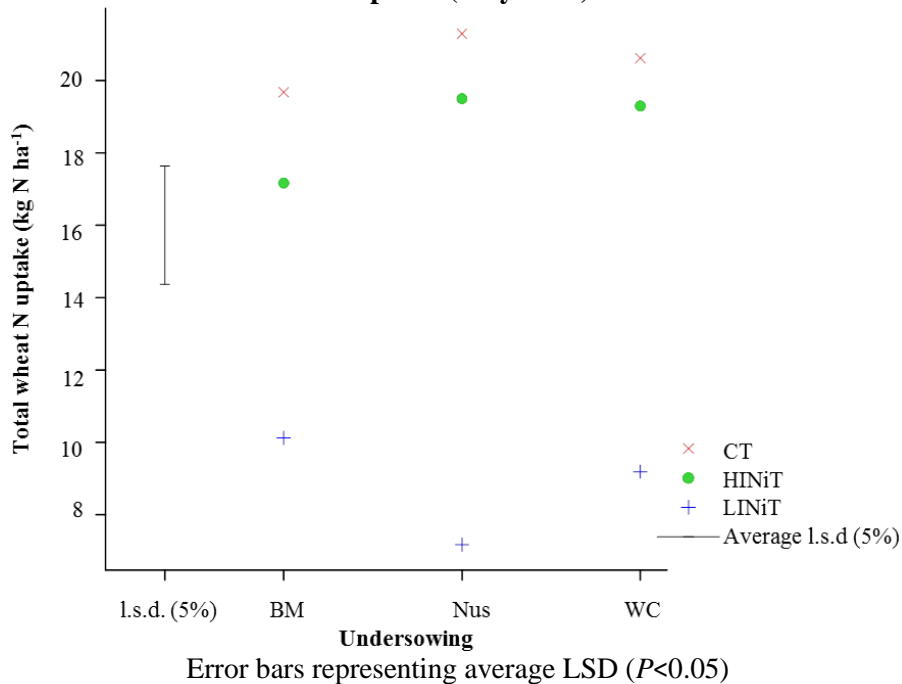
At the July assessment, wheat DM and total wheat N uptake were not significantly affected by cultivation techniques (Table 7). On the contrary, N fertilisation treatments significantly increased ($P<0.001$) wheat DM, compared with unfertilised condition, while N uptake significantly increased ($P<0.001$) with increasing N rate application (Table 4.7). No significant effects of undersowing or treatment interactions were observed on wheat biomass and N uptake at the July assessment.

Table 4. 7. Effect of cultivation techniques and nitrogen fertilisation on spring wheat biomass and N uptake (July 2013)

	Wheat DM (t ha^{-1}) July	Total wheat N uptake (kg N ha^{-1}) July
CT	6.93a	125.40a
HINiT	7.56a	128.40a
LINiT	6.66a	143.20a
SED (4 df)	*0.58*	*11.27*
P	*ns*	*ns*
N0	5.25a	70.90a
N70	7.19b	125.90b
N140	7.82b	154.50c
N210	7.94b	178.10d
SED (18 df)	*0.45*	*11.12*
P	*****	*****

Values followed by same letter, do not differ significantly at *P<0.05.* ****= P<0.001; and *ns*= no significant

4.3.4. Mid-season legume biomass and nitrogen accumulation

Cultivation techniques treatments showed no significant effect on legume DM and N uptake during both growth assessments (Table 4.8). N fertilisation treatments only affected legume biomass in July, resulting in a significant reduction ($P<0.05$) of DM when N was applied, regardless of the rate. Moreover, legume N uptake was not significantly affected by N fertilisation at any assessment time.

No significant effects of undersowing or treatment interactions were observed on legume biomass and N uptake.

Table 4. 8. Effect of cultivation techniques and nitrogen fertilisation on legume biomass and N uptake (May and July 2013)

	Legume DM (t ha^{-1}) May	Legume N uptake (kg N ha^{-1}) May	Legume DM (t ha^{-1}) July	Legume N uptake (kg N ha^{-1}) July
CT	0.0001a	0.001a	0.0580a	1.343a
HINiT	0.0010a	0.0362a	0.0196a	0.390a
LINiT	0.0004a	0.0153a	0.0144a	0.334a
SED (4 df)	*0.0005*	*0.0196*	*0.0245*	*0.6259*
P	*ns*	*ns*	*ns*	*ns*
N0	0.0002a	0.0087a	0.0809b	1.608a
N70	0.0004a	0.0130a	0.0216a	0.535a
N140	0.0002a	0.0076a	0.0103a	0.291a
N210	0.0011a	0.0394a	0.0099a	0.322a
SED (18 df)	*0.0005*	*0.0186*	*0.0242*	*0.5142*
P	*ns*	*ns*	*	*ns*

Values followed by same letter, do not differ significantly at *P<0.05*. *= *P<0.05*; and *ns*= no significant

4.3.5. Mid-season total weed biomass and nitrogen accumulation

<u>May assessment</u>

HINiT significantly resulted (*P*<0.05) in a greater total weed biomass than CT and LINiT, at the May assessment (Table 4.9). No significant effect of cultivation techniques was observed on total weed N uptake. N fertilisation, undersowing or any treatment interaction did not significantly affect weed DM and total weed N uptake (Table 4.9).

<u>July assessment</u>

Among cultivation techniques, HINiT significantly increased (*P*<0.05) total weed DM, particularly when compared with CT (Table 9). Weed N uptake was significantly lower (*P*<0.05) under CT when compared with HINiT and LINiT (Table 4.9). N fertiliser application significantly increased (*P*<0.001) weed DM and N uptake regardless of the

rate used compared with N0. Undersowing resulted in a non-significant effect on total weed DM or weed N yield at July assessment.

Table 4. 9. Effect of cultivation techniques and nitrogen fertilisation on weed biomass and N uptake (May and July 2013)

	Total weed DM (t ha^{-1}) May	Total weed N uptake (kg N ha^{-1}) May	Total weed DM (t ha^{-1}) July	Total weed N uptake (kg N ha^{-1}) July
CT	0.0289a	1.11a	0.8600a	22.75a
HINiT	0.0540b	1.95a	1.9980b	44.07b
LINiT	0.0184a	0.83a	1.4560ab	38.40b
SED (4 df)	*0.0084*	*0.33*	*0.2583*	*5.09*
P	*	*ns*	*	*
N0	0.0364a	1.38a	0.9100a	13.19a
N70	0.0410a	1.55a	1.6320b	36.96b
N140	0.0303a	1.19a	1.7530b	44.98b
N210	0.0275a	1.08a	1.4570b	45.16b
SED (18 df)	*0.0063*	*0.24*	*0.1554*	*4.25*
P	*ns*	*ns*	***	***

Values followed by same letter, do not differ significantly at *P<0.05. *= P<0.05*; and *ns*= no significant

Due to significant interactions (*P*<0.001), HINiT increased weed biomass when N70 or N140 were applied, specifically when compared with N0 (Figure 4.7). LINiT increased weed DM with N140 and N210 applications compared with N0. No significant differences were observed under CT between N rates.

Figure 4. 7. Effect of cultivation techniques and nitrogen fertilisation interaction on weed biomass (July 2013)

Error bars representing average LSD (*P*<0.05)
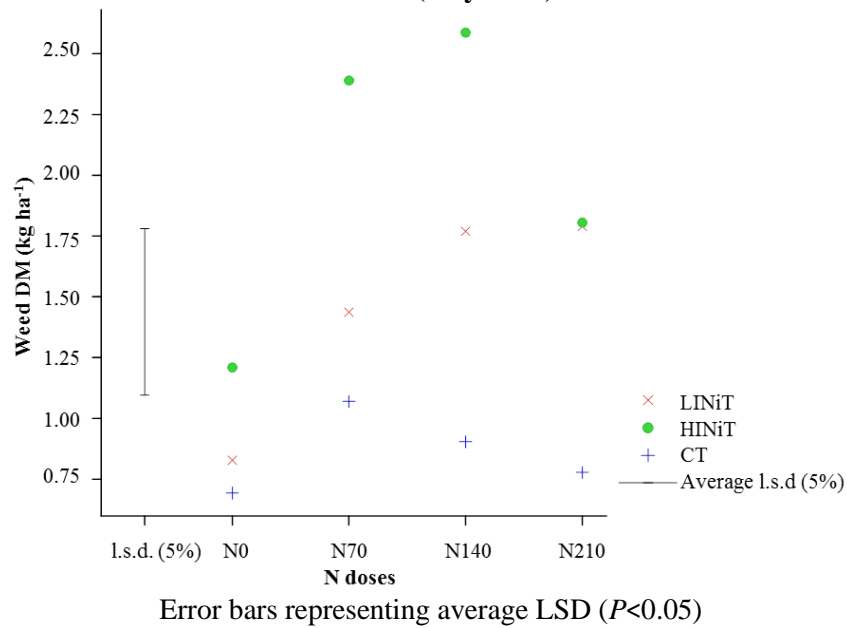
Due to significant interactions (*P*<0.001), BM and WC increased weed DM under non-inversion tillage treatments compared with CT. However, under Nus, HINiT resulted in higher weed DM than CT and LINiT (Figure 4.8).

Figure 4. 8. Effect of cultivation techniques and undersowing interaction on weed biomass (July 2013)

Error bars representing average LSD (*P*<0.05)
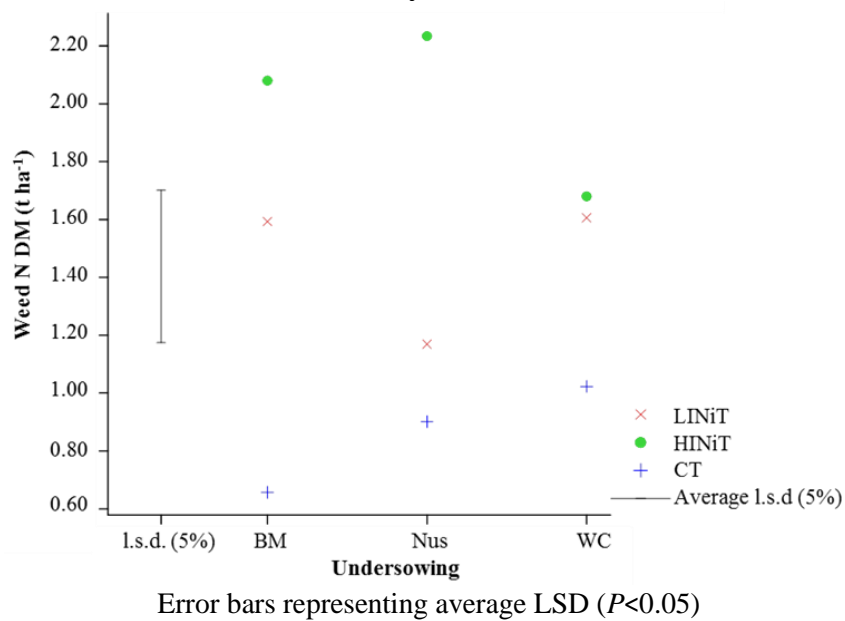
Additionally, WC increased weeds DM under fertilised conditions regardless of the rate (Figure 4.9). Under Nus, weed DM was higher at N140, compared with N0. BM significantly increased weed DM when N70 and N140 were applied, compared specifically with the unfertilised treatment.

Figure 4. 9. Effect of nitrogen fertilisation and undersowing interaction on weed biomass (July 2013)
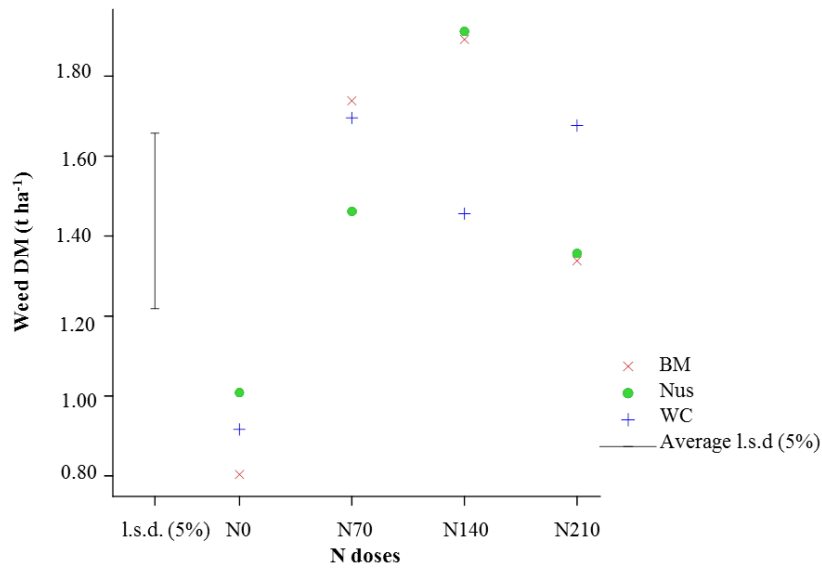
Error bars representing average LSD (*P*<0.05)

Cultivation techniques significantly interacted (*P*<0.05) with N fertilisation, resulting in higher weed N uptake under HINiT and LINiT than CT when either N140 or N210 were applied (Figure 4.10). No significant differences were observed between cultivation techniques at N0.

Figure 4. 10. Effect of cultivation techniques and nitrogen fertilisation on weed N uptake (July 2013)

Error bars representing average LSD (*P*<0.05)
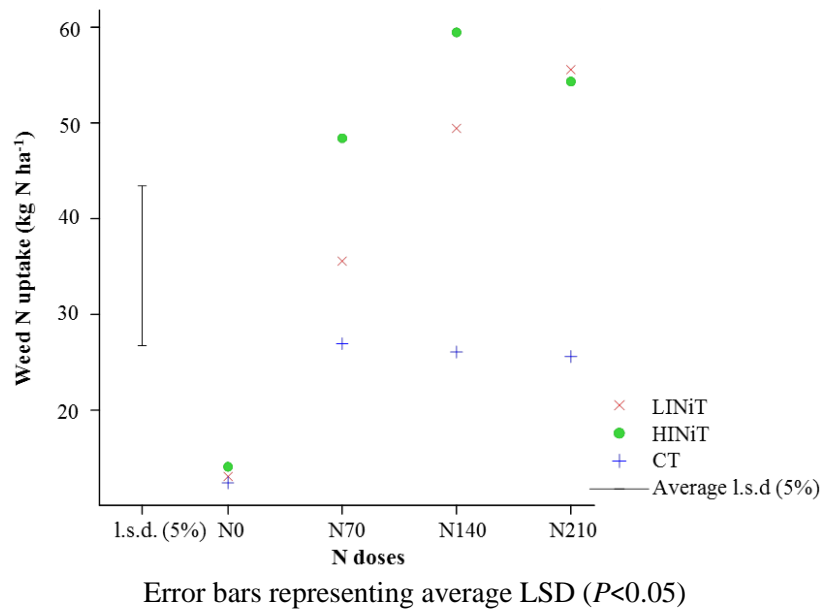
Cultivation techniques also significantly interacted (*P*<0.01) with undersowing, with BM and WC resulting in a significant lower weed N uptake under CT than HINiT and LINiT, while Nus resulted in lower weed N uptake following either CT or LINiT than HINiT (Figure 4.11).

Figure 4. 11. Effect of cultivation techniques and undersowing on weed N uptake (July 2013)

Error bars representing average LSD (*P*<0.05)
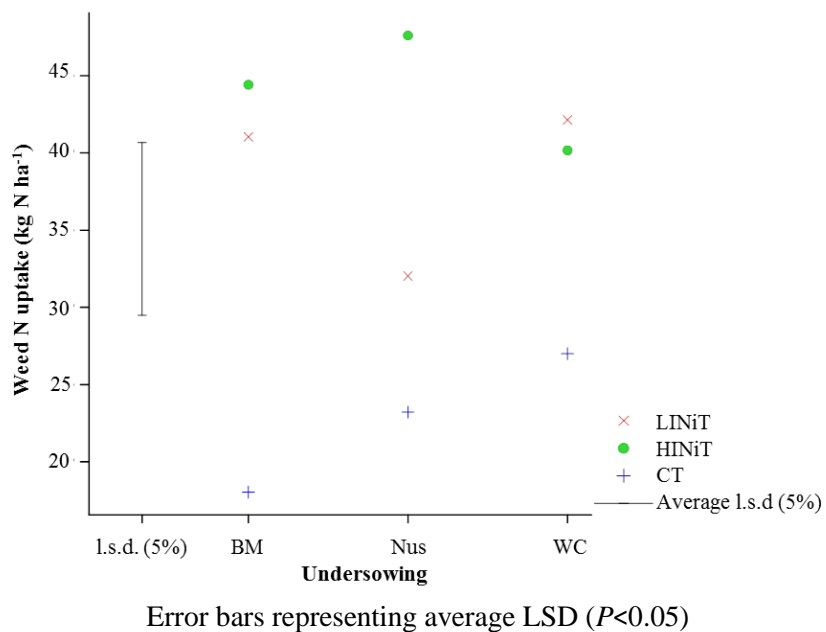
4.3.6. Weed species composition

Irrespective of management treatments, a total of 39 weed species were recorded during the 2013 cropping season. At both growth assessment times, weeds were separated by species and grouped into broadleaf and grass weeds. In May, no grass weeds were observed, and total weed DM was mainly broadleaved weeds (Table 4.9).

At the July assessment, HINiT significantly increased ($P<0.05$) broadleaf weed DM compared with CT and LINiT (Table 4.10). Moreover, a significant increase ($P<0.001$) of broadleaf weed DM was observed with applications of 70 and 140 kg N ha^{-1}. Grass weed were not significantly affected by any treatment or interactions at this assessment time.

Table 4. 10. Effect of cultivation techniques and nitrogen fertilisation on weed species biomass (July 2013)

	Broadleaf weed DM (t ha^{-1}) July	Grass weed DM (t ha^{-1}) July
CT	0.772a	0.089a
HINiT	1.673b	0.325a
LINiT	0.949a	0.507a
SED (4 df)	*0.183*	*0.15*
P	*	*ns*
N0	0.778a	0.131a
N70	1.409b	0.223a
N140	1.318b	0.436a
N210	1.019a	0.438a
SED (18 df)	*0.124*	*0.133*
P	***	*ns*

Values followed by same letter, do not differ significantly at *P<0.05*. *= P<0.05; ****=P<0.001 and *ns*= no significant

No significant undersowing treatments effect was observed for either broadleaved weeds or grass weeds at any assessment time.

Furthermore, HINiT significantly increased ($P<0.05$) broadleaf weeds when N70 and N140 was applied, compared with CT and LINiT (Figure 4.12).

Figure 4. 12. Effect of cultivation techniques and nitrogen fertilisation on broadleaved weeds biomass (July 2013)

Error bars representing average LSD (*P*<0.05)
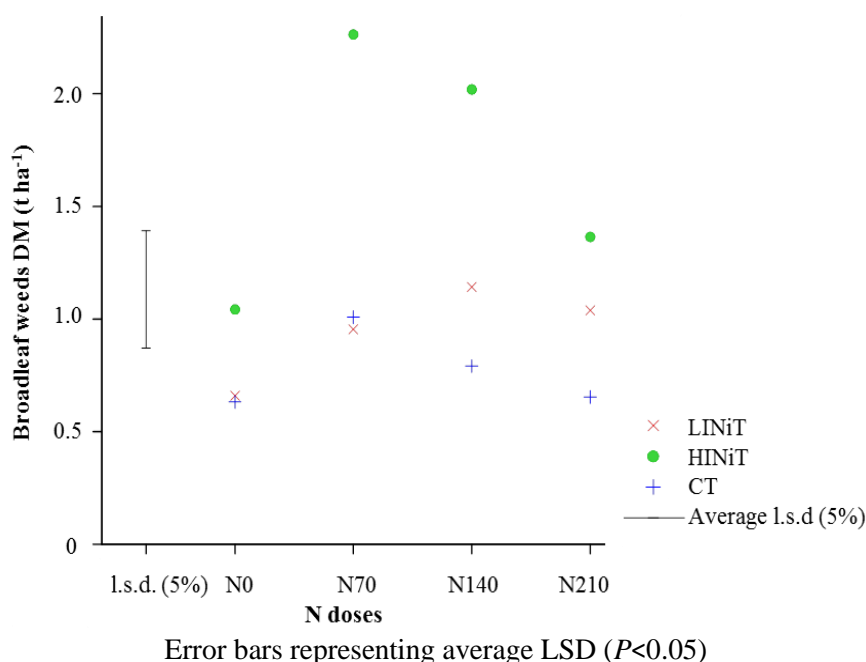
Among weed species, five grasses and 33 broadleaved weed species were recorded. Weed species recorded in May were also present in July. To prevent over-counting, weed biomass by species was analysed only from the July assessment. The list of all weed species recorded can be found in Appendix 2.

The dominant broadleaf weed species were *Stellaria media* L., *Fallopia convolvulus* L. and *Sinapsis arvensis* L., accounting for 29.8%, 12.1% and 9.7% of the total weed biomass recorded. Dominant grass weeds were *Avena fatua* L. and *Lolium perenne* L. constituting 11.9% and 8.1% of the total weed biomass.

Within all the species only *Stellaria media, Lolium perenne* and *Avena fatua* were significantly affected by management treatments. Other species were not significantly affected by any treatment, or occurred too infrequently to permit treatment effects to be appropriately tested.

Stellaria media DM significantly increased (*P*<0.05) under HINiT compared with CT and LINiT, while its biomass significantly increased (*P*<0.05) with N70 and N140 (Table 4.11).

Table 4. 11. Effect of cultivation techniques and nitrogen fertilisation on *Stellaria media* L. and *Lolium perenne* L. biomass

	Stellaria media L. DM (t ha^{-1})	*Lolium perenne* L. DM (t ha^{-1})
CT	0.2251a	0.0155a
HINiT	0.8544b	0.0318a
LINiT	0.1969a	0.3010b
SED (4 df)	*0.1327*	*0.0436*
P	*	**
N0	0.2422a	0.0717a
N70	0.5396b	0.0916a
N140	0.5254b	0.1865b
N210	0.3947ab	0.1146ab
SED (18 df)	*0.0994*	*0.036*
P	*	*

Values followed by same letter, do not differ significantly at *P<0.05; *= P<0.05*; ***= P<0.01*; and *ns*= no significant

Furthermore, due to interactions, HINiT significantly increased (*P<0.05*) *Stellaria media* biomass with either N70 or N140 applications compared with N0 and N210 (Figure 4.13).

Figure 4. 13. Effect of cultivation techniques and nitrogen fertilisation interaction on *Stellaria media* L. biomass (July 2013)

Error bars representing average LSD (*P<0.05*)
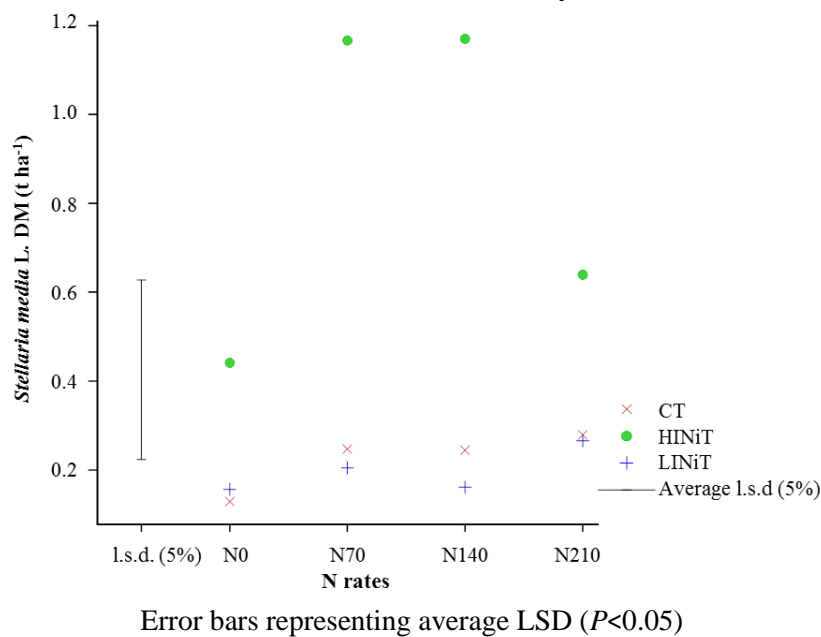
Lolium perenne DM was greater under LINiT (*P*<0.01) compared to CT and HINiT, and N140 significantly increased (*P*<0.05) its DM compared specifically with N0 (Table 4.11). Under LINiT, *Lolium perenne* biomass was significantly higher (*P*<0.01) when N140 was applied compared with any other N rate (Figure 4.14). Additionally, under fertilised conditions LINiT resulted in higher *Lolium perenne* DM compared with CT and HINiT, while non-significant effects were observed between cultivation techniques at N0.

Figure 4. 14. Effect of cultivation techniques and nitrogen fertilisation interaction on *Lolium perenne* L. biomass (July 2013)

Error bars representing average LSD (*P*<0.05)
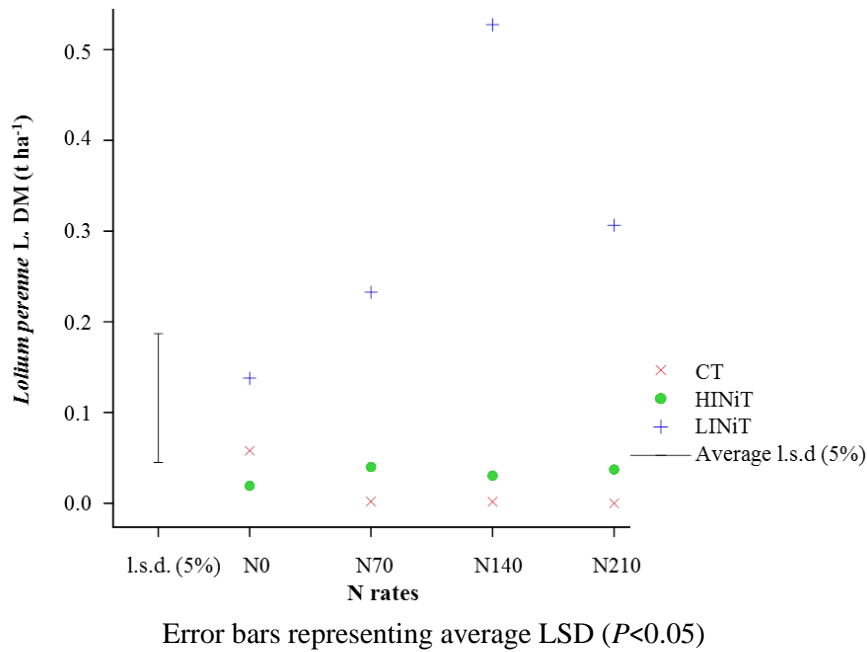
Furthermore, under LINiT, *Lolium perenne* DM increased when BM was undersown compared with WC and Nus (Figure 4.15).

Figure 4. 15. Effect of cultivation techniques and undersowing interaction on *Lolium perenne* L. biomass (July 2013)

Error bars representing average LSD (*P*<0.05)
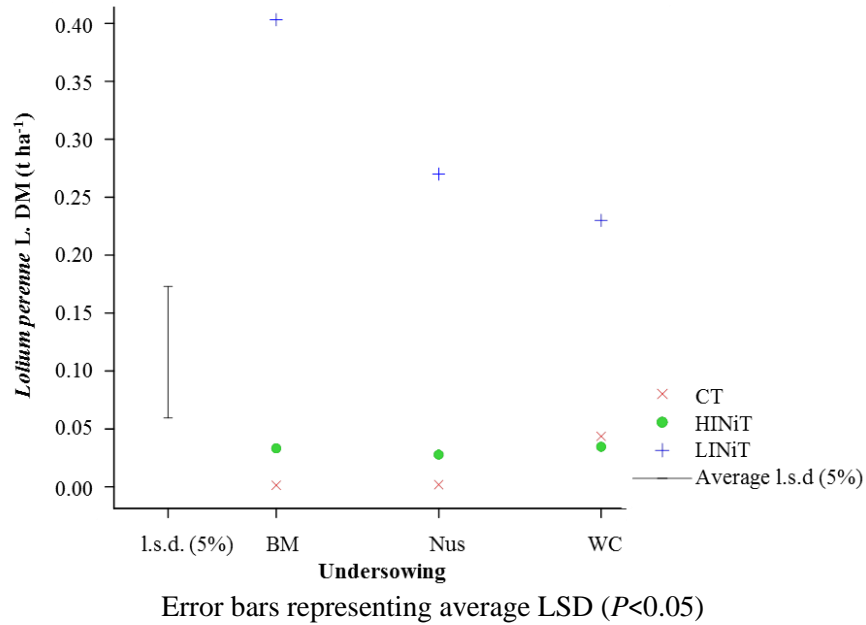
Avena fatua DM was greater (*P*<0.01) under HINiT compared with CT and LINiT at Nus (Figure 4.16). Higher *Avena fatua* DM was also found under HINiT when BM was undersown or Nus compared with WC.

Figure 4. 16. Effect of cultivation techniques and undersowing interaction on *Avena fatua* L. biomass (July 2013)

Error bars representing average LSD (*P*<0.05)
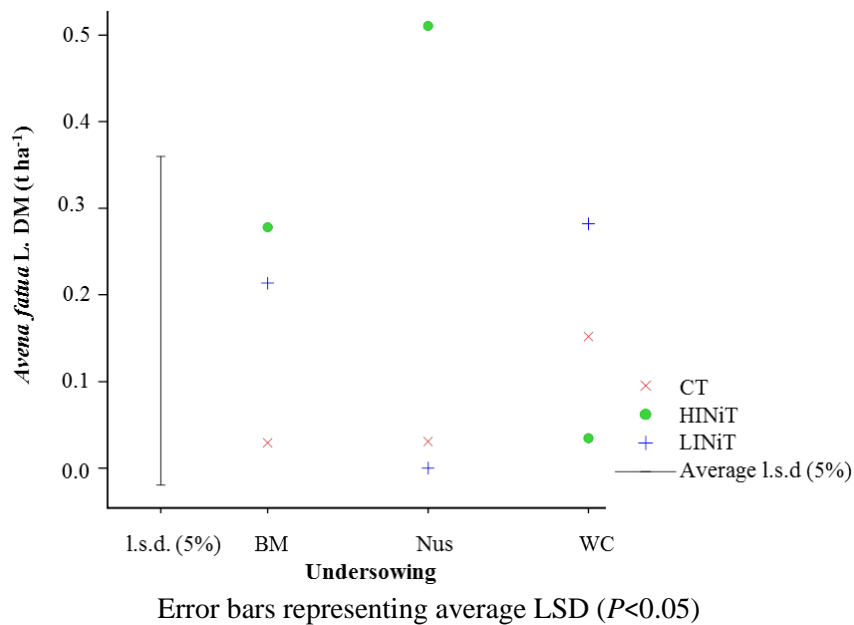
4.3.7. Plant height and ears number

The different cultivation techniques gave no significant effect on wheat height (Table 4.12). However, significantly ($P<0.001$) taller plants were recorded with 210 kg N ha^{-1}, when specifically compared with N0 and N70. There was no significant effect of undersowing and no treatment interactions on wheat height.

Wheat ear number per m^2 was significantly increased ($P<0.01$) under CT and HINiT compared with LINiT (Table 4.12). Nevertheless, there were no significant effects of N fertilisation rates, undersowing and any treatments interactions on total wheat ears number.

Table 4. 12. Cultivation techniques and nitrogen fertilisation effects on wheat height and wheat ear number

	Plant height (cm)	Ears (number m^{-2})
CT	95.52a	596.10b
HINiT	96.72a	617.60b
LINiT	94.66a	484.00a
SED (4 df)	*1.38*	*25.10*
P	*ns*	****
N0	87.59a	597.00a
N70	96.31b	506.50a
N140	98.47bc	581.10a
N210	99.36c	579.10a
SED (18 df)	*1.37*	*49.53*
P	*****	*ns*

Values followed by same letter, do not differ significantly at *P<0.05;* **= *P<0.01;*
***=*P<0.001;* and *ns*= no significant

4.3.8. Disease scoring

Assessments showed low incidence of leaf blotch (*Zymoseptoria tritici* Desm. Quaedvlieg & Crous) and take-all (*Gaeumannomyces graminis* var *tritici*). No significant effect of any treatments or treatments interaction was observed, and no results are therefore presented.

4.3.9. Final biological harvest

Ear, straw and total wheat biomass

Cultivation techniques did not significantly affect ear, straw or total wheat DM (Table 4.13). However, N fertilisation treatments only significantly affected ($P<0.01$) straw DM, resulting in an increase in biomass production when N210 was applied, particularly when compared with N0. There was no significant effect of undersowing or any treatment interaction on ear, straw biomass and total wheat DM.

Table 4. 13. Effect of cultivation techniques and nitrogen fertilisation on spring wheat ears, straw and total wheat biomass

	Ears DM (t ha^{-1})	Straw DM (t ha^{-1})	Total wheat DM (t ha^{-1})
CT	7.13a	5.22a	13.33a
HINiT	7.17a	5.40a	13.73a
LINiT	7.59a	4.93a	13.38a
SED (4 df)	*0.28*	*0.25*	*0.763*
P	*ns*	*ns*	*ns*
N0	6.88a	4.50a	12.28a
N70	6.98a	4.98ab	13.26a
N140	7.89a	5.45bc	14.11a
N210	7.44a	5.81c	14.29a
SED (18 df)	*0.63*	*0.34*	*0.877*
P	*ns*	***	*ns*

Values followed by same letter, do not differ significantly at *P<0.05;* ***= P<0.01*, and *ns*= no significant

TGW, grains per ear and grain yield

Cultivation techniques did not significantly affect thousand grain weight (TGW) (Table 4.14). Increasing N fertilisation rates significantly reduced ($P<0.001$) TGW, with 29.31 g (LSD 2.07) observed when N210 was applied, compared with 35.52 g under N0. Additionally, CT significantly interacted ($P<0.01$) with Nus resulting in lower TGW compared with non-inversion tillage treatments (Figure 4.17).

The number of grains per ear was significantly higher under LINiT ($P<0.01$) than with CT and HINiT (Table 4.14). In addition, the N fertilisation, regardless of the N rate, also significantly increased ($P<0.05$) grain number per ear compared with N0 (Table 4.14). Yet undersowing, or any other treatment interactions, did not significantly affect number of grains per ears.

Overall, final spring wheat grain yield mean obtained in 2013 cropping season was 5.65 t ha^{-1}. Cultivation techniques significantly affected ($P<0.05$) grain yield with LINiT resulting in a higher yield than HINiT while showing statistically comparable yield with CT (Table 4.14). No significant effect was observed by N fertilisation, undersowing or any treatments interactions on final grain yield.

Table 4. 14. Effect of cultivation techniques and nitrogen fertilisation on TGW, grains per ear, final grain yield and harvest index

	TGW (g)	Grain per ears	Grain yield (t ha^{-1})	HI (%)
CT	31.94a	30.63a	5.58ab	45.77ab
HINiT	32.40a	29.29a	5.30a	43.81a
LINiT	32.79a	37.96b	6.08b	48.61b
SED (4 df)	*0.75*	*0.97*	*0.21*	*1.094*
P	*ns*	**	*	*
N0	35.52c	28.59a	5.61a	50.33c
N70	33.03b	33.73b	5.50a	46.03b
N140	31.65b	33.70b	5.86a	45.21ab
N210	29.31a	34.48b	5.63a	42.69a
SED (18 df)	*0.99*	*1.76*	*0.44*	*1.479*
P	***	*	*ns*	***

Values followed by same letter, do not differ significantly at *P<0.05;* *= *P<0.05;***= *P<0.01,* and *ns*= no significant

Harvest index (HI) was significantly affected ($P<0.05$) by cultivation techniques treatments, resulting in greater HI under LINiT, compared specifically with HINiT (Table 4.14). Increasing N fertilisation rate significantly decreased ($P<0.001$) HI, with N0 resulting in the highest HI (Table 4.14).

Figure 4. 17. Effect of cultivation techniques and undersowing interaction on spring wheat TGW

Error bars representing average LSD (*P*<0.05)
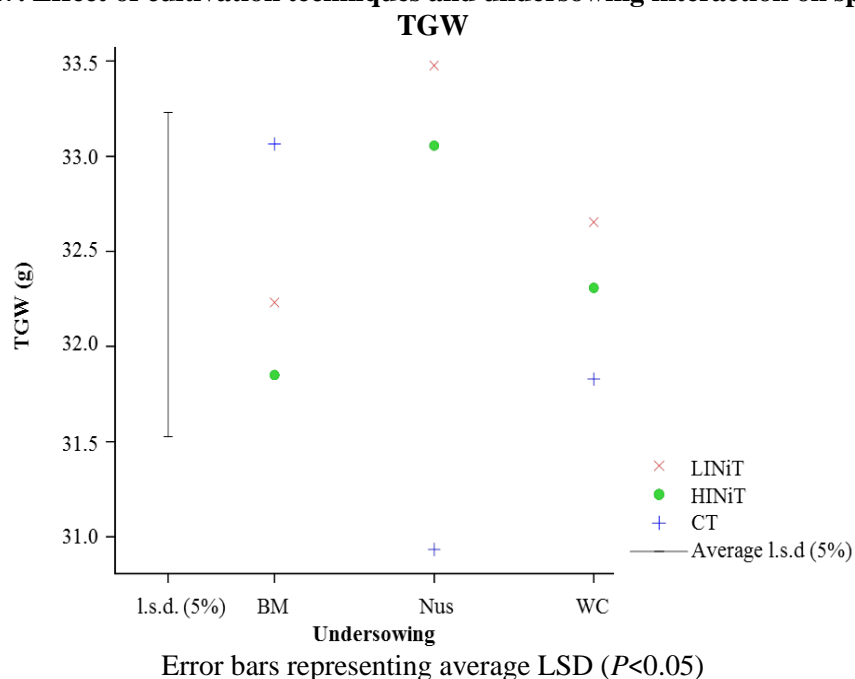
Wheat nitrogen yield

The average total wheat N uptake across treatments was 150.5 kg ha^{-1}. Cultivation techniques did not significantly affect wheat N uptake (Table 4.15). N fertilisation treatments significantly affected (*P*<0.001) wheat N uptake resulting in lower uptake with N0 and N70, compared with N140 and N210 (Table 4.15).

Total grain N uptake was significantly higher (*P*<0.05) with LINiT compared with CT and HINiT (Table 4.15). Furthermore, grain N uptake was significantly lower (*P*<0.001) under N0 compared specifically with N210.

Regardless of management treatments, the average grain protein obtained was 12.28%. LINiT significantly increased (*P*<0.001) grain protein content (13.02%) followed by CT (12.11%) and then by HINiT (11.71%) (LSD 0.33) (Table 4.15). Increases of N rates resulted in a highly significant effect (*P*<0.001) on grain protein with N210 producing 14.46% of grain protein.

N harvest index (NHI) was not significantly affected by cultivation treatments. However, application of 210 kg N ha^{-1} resulted in a significant lower (*P*<0.001) NHI compared particularly with unfertilised conditions (Table 4.15).

Table 4. 15. Effect of cultivation techniques and nitrogen fertilisation on spring wheat N uptake, grain protein and N harvest index

	Total wheat N uptake (kg ha⁻¹)	Total grain N uptake (kg ha⁻¹)	Grain protein (%)	NHI (%)
CT	144.70a	118.30a	12.11b	82.07a
HINiT	140.0a	113.90a	11.71a	80.77a
LINiT	166.7a	137.90b	13.02c	82.48a
SED (4 df)	*8.16*	*6.61*	*0.12*	*0.64*
P	*ns*	***	***	*ns*
N0	120.60a	102.6a	10.12a	84.56c
N70	137.7a	114.0ab	11.87b	82.44bc
N140	163.6b	135.6bc	12.68b	82.13b
N210	180.0b	141.3c	14.46c	77.95a
SED (18 df)	*12.26*	*10.67*	*0.46*	*1.11*
P	***	***	***	***

Values followed by same letter, do not differ significantly at *P<0.05; *= P<0.05; ***=P<0.001;* and *ns*= no significant

There were no significant effects of undersowing or any treatments interactions on total wheat and grain N uptake, grain protein and NHI.

<u>Wheat N efficiency</u>

Regardless of the treatments, N-use efficiency (NUE) was on average 30 kg kg⁻¹. Cultivation treatments did not exert a significant effect on NUE and N uptake efficiency (NUpE). However, N utilisation efficiency (NUtE) was significantly higher (*P*<0.05) under CT and HINiT than with LINiT (Table 4.16).

N fertilisation treatments significantly affected (*P*<0.001) NUE, NUpE and NUtE (Table 4.16). NUE decreased when increasing N rates and a similar trend was observed for NUpE although no significant differences were found between N140 and N210. NUtE decreased with increasing N rates but no significant differences were observed between N70 and N140 (Table 4.16).

Undersowing treatments significantly affected (*P*<0.05) NUE, resulting in greater NUE under Nus specifically when compared with BM, although, no significant effects were

observed on NUpE or NUtE (Table 4.16). No significant differences were found between any treatment interactions on N-use efficiency parameters.

Table 4. 16. Effect of cultivation techniques, nitrogen fertilisation and undersowing on spring wheat N-efficiency parameters

	NUE (kg kg^{-1})	NUpE (kg kg^{-1})	NUtE (kg kg^{-1})
CT	31.67a	0.761a	40.30b
HINiT	30.43a	0.702a	40.84b
LINiT	27.82a	0.728a	37.02a
SED (4 df)	*1.545*	*0.044*	*0.846*
P	*ns*	*ns*	***
N0	49.08d	0.999c	48.94c
N70	30.07c	0.744b	40.29b
N140	23.48b	0.626a	37.30b
N210	17.26a	0.553a	31.02a
SED (18 df)	*2.289*	*0.042*	*1.995*
P	*****	*****	*****
BM	28.41a	0.709a	38.76a
Nus	31.72b	0.759a	40.04a
WC	29.78ab	0.724a	39.37a
SED (44 df)	*1.202*	*0.029*	*0.61*
P	**	*ns*	*ns*

Values followed by same letter, do not differ significantly at *P≤0.05; *= P<0.05; ***= P<0.001; and *ns*= no significant

Weed and legume biomass and nitrogen yield

Total weed biomass and N uptake were not significantly affected by cultivation techniques treatments (Table 4.17). Although, no significant effects of N fertilisation were observed on weed DM, weed N uptake was significantly lower ($P<0.05$) with N0 than with N140 and N210. No significant effect of undersowing or any treatment interaction on weed DM or N uptake was observed.

CT resulted in significant higher ($P<0.01$) legume DM and N uptake than HINiT and LINiT (Table 4.17). N0 resulted in significantly higher ($P<0.001$) legume biomass and N uptake compared with N fertilised treatments.

Table 4. 17. Effect of cultivation techniques and nitrogen fertilisation on weed and legume biomass and N uptake (Harvest 2013)

	Total weed DM (t ha^{-1})	Total weed N uptake (kg ha^{-1})	Legume DM (t ha^{-1})	Total legume N uptake (kg ha^{-1})
CT	0.874a	15.76a	0.112b	3.300b
HINiT	1.217a	20.06a	0.042a	1.381a
LINiT	1.329a	25.05a	0.004a	0.117a
SED (4 df)	*0.2656*	*5.82*	*0.0154*	*0.466*
P	*ns*	*ns*	**	**
N0	0.934a	13.60a	0.177b	5.399b
N70	1.291a	20.23ab	0.015a	0.453a
N140	1.301a	24.46b	0.014a	0.417a
N210	1.033a	24.46b	0.004a	0.129a
SED (18 df)	*0.2164*	*3.741*	*0.017*	*0.59*
P	*ns*	*	***	***

Values followed by same letter, do not differ significantly at *P<0.05;* *= *P*<0.05; **= *P*<0.01, ***= *P*<0.001; and *ns*= no significant

Due to significant interactions ($P<0.001$), at N0, CT significantly increased the legume DM (Figure 4.18) and N uptake (Figure 4.19) compared with HINiT and then by LINiT. No significant effects were observed between any other N rate and cultivation techniques interaction.

Figure 4. 18. Effect of cultivation techniques and nitrogen fertilisation interaction on legumes biomass (Harvest 2013)
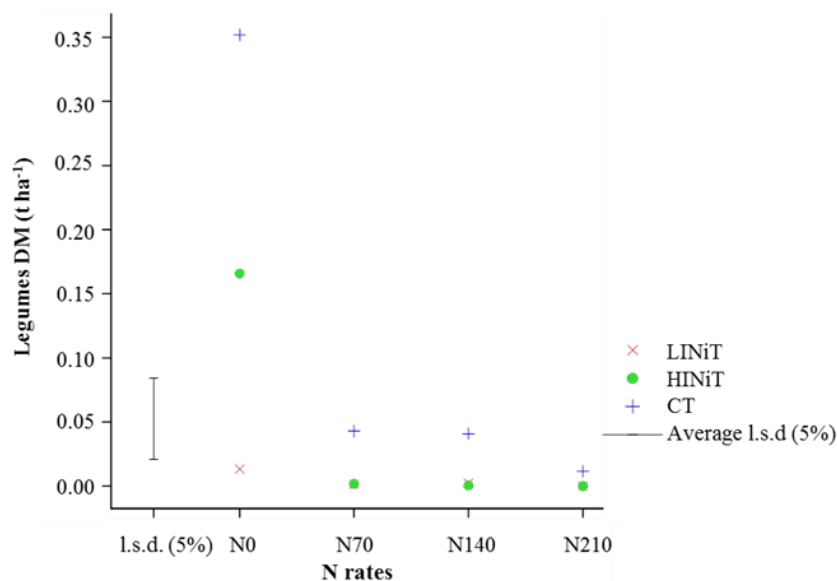
Error bars representing average LSD (*P<0.05*)

Figure 4. 19. Effect of cultivation techniques and nitrogen fertilisation interaction on total legumes N uptake (Harvest 2013)

Error bars representing average LSD (*P*<0.05)
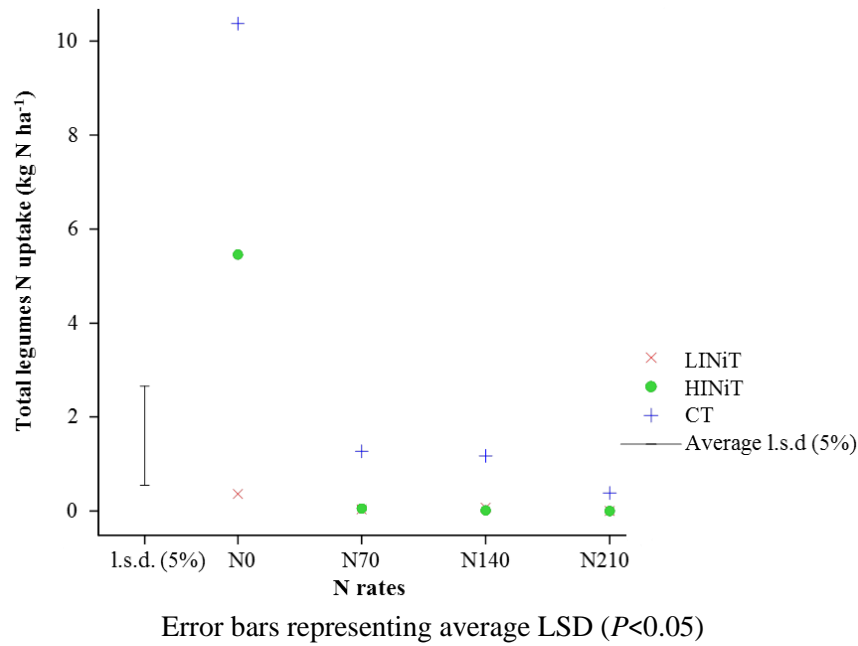
Significantly higher (*P*<0.05) legume N uptake was observed with N0 under Nus, compared with BM and WC (Figure 4.20).

Figure 4. 20. Effect of undersowing and nitrogen fertilisation interaction on total legumes N uptake (Harvest 2013)

Error bars representing average LSD (*P*<0.05)
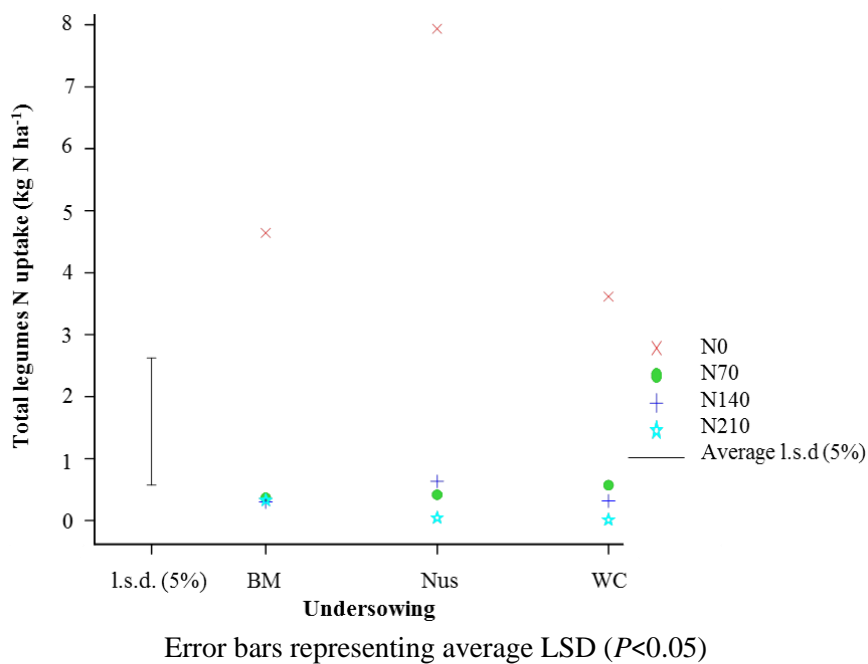
Total non-wheat (legumes plus weeds) DM and N uptake were not significantly affected by cultivation techniques, N fertilisation rates, undersowing or any treatment interaction, and the results are not, therefore, presented.

4.3.10. Soil mineral nitrogen

Throughout the assessments, cultivation technique effects on SMN were only evident in May, resulting in a significantly higher (P<0.001) SMN under CT (146.9 kg N ha^{-1}) and LINiT (141.5 kg N ha^{-1}) compared with HINiT (114.6 kg N ha^{-1}) (LSD 9.31) (Figure 4.21).

Figure 4. 21. Soil mineral nitrogen (kg N ha^{-1}) under three cultivation techniques

Error bars representing LSD (P<0.05) at each month of assessment
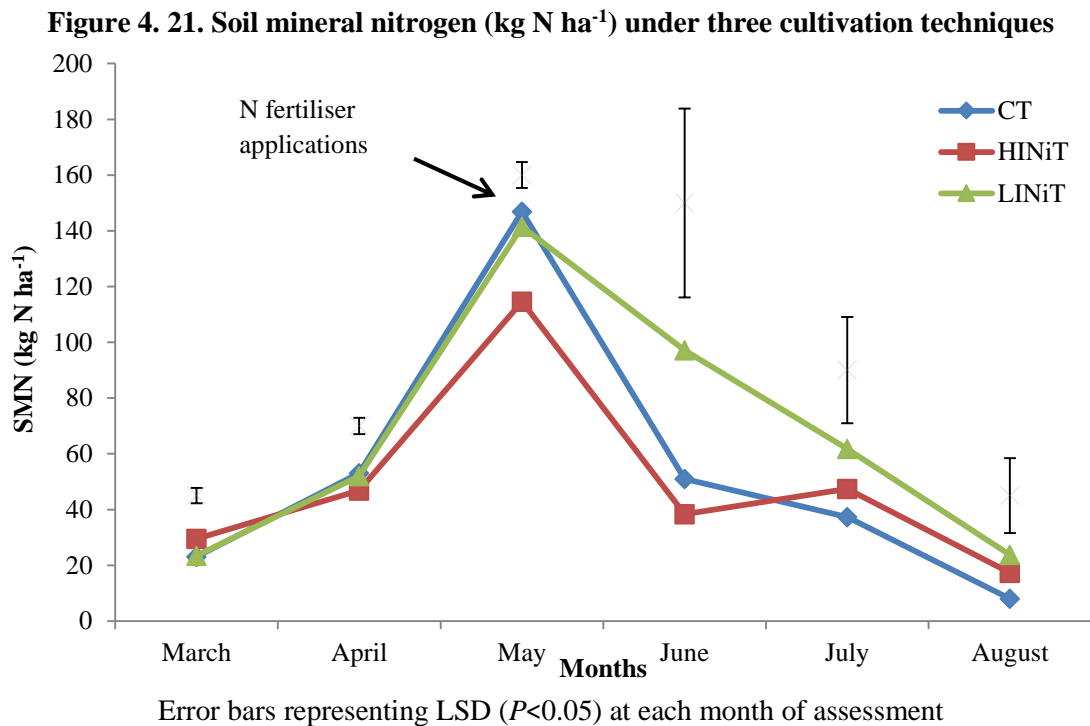
N fertilisation treatments resulted in a strong significant effect (P<0.001) on SMN content throughout all the assessments times (Figure 4.22). In May, higher SMN contents were observed under high N rates, where N210 resulted on 226.5 kg N ha^{-1} while N0 showed 15.60 kg N ha^{-1} (LSD 30.81). In June and July, lower SMN content was recorded when either N0 or N70 were applied, compared with N140 and N210. At the end of the season, August, N210 showed the highest SMN content (43.81 kg N ha^{-1}).

Figure 4. 22. Soil mineral nitrogen (kg N ha⁻¹) under four nitrogen fertilisation treatments

Error bars representing LSD ($P<0.05$) at each month of assessment
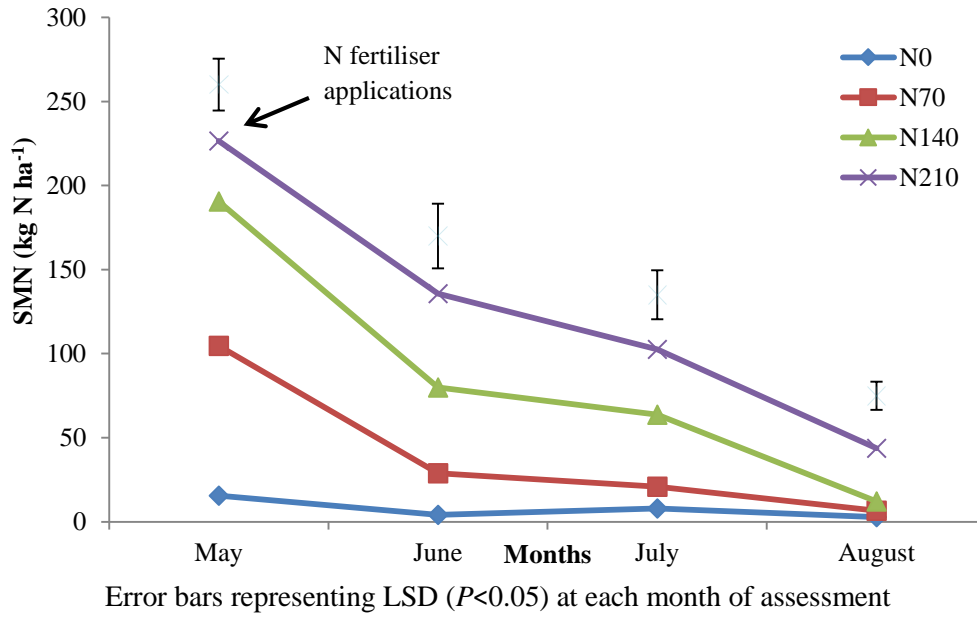
There was not a significant effect of undersowing treatments on SMN content throughout the assessments. However, at June assessment, due to interactions, WC and Nus treatments resulted in higher SMN content under LINiT than CT and HINiT (Figure 4.23). No significant differences were found when BM was undersown under any tillage treatment.

Figure 4. 23. Effect of cultivation techniques and undersowing interaction on soil mineral nitrogen (kg N ha^{-1}) (June 2013)

Error bars representing average LSD ($P<0.05$)
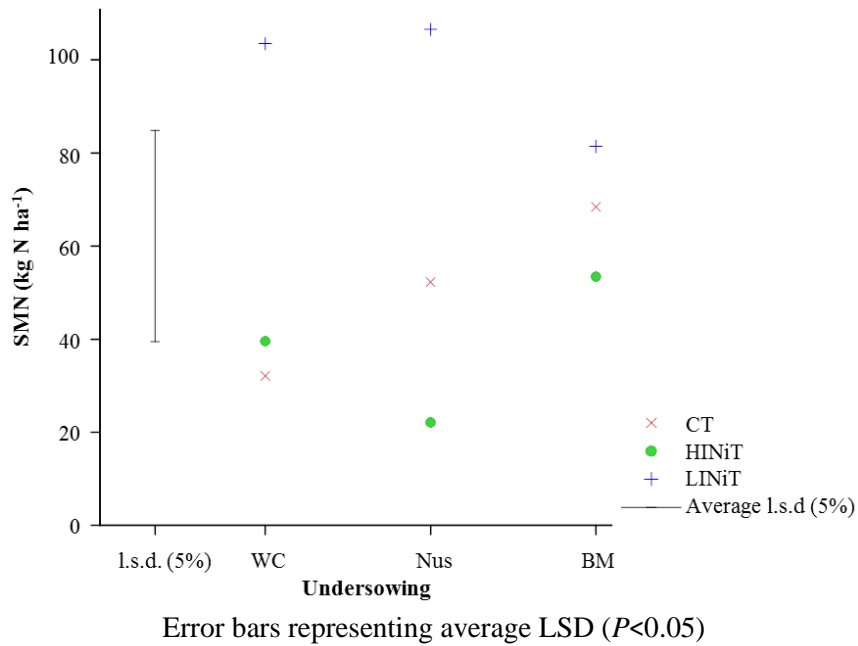
Under WC, the highest SMN was observed with N210 (Figure 4.24). Under Nus, the highest SMN was recorded with either N140 or N210. In the case of BM, SMN content increased when increasing N rate although no differences were observed between N70 and N0.

Figure 4. 24. Effect of nitrogen fertilisation and undersowing interaction on soil mineral nitrogen (kg N ha^{-1}) (June 2013)

Error bars representing average LSD ($P<0.05$)
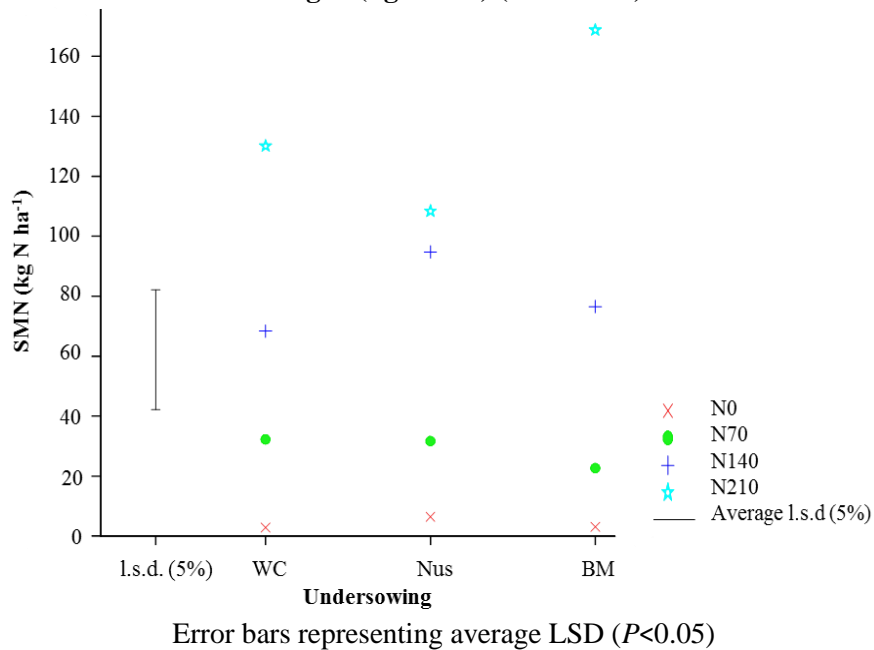
At the June assessment, there was a significant cultivation *x* N fertilisation *x* undersowing interaction affecting SMN content (Figure 4.25). When N140 was applied under Nus, LINiT resulted in higher SMN content than CT and HINiT. Likewise, at N210 with WC, LINiT resulted in higher SMN content than CT and HINiT. Under N210 with undersown BM, CT resulted in higher SMN compared with HINiT and statistically similar to LINiT. In addition, LINiT resulted in higher SMN content than HINiT under Nus at N210. No significant differences were observed between treatments interactions under N0 or with N70 rate.

Figure 4. 25. Effect of cultivation techniques, nitrogen fertilisation and undersowing interaction on soil mineral nitrogen (kg N ha^{-1}) (June 2013)

Error bars representing average LSD (*P*<0.05)
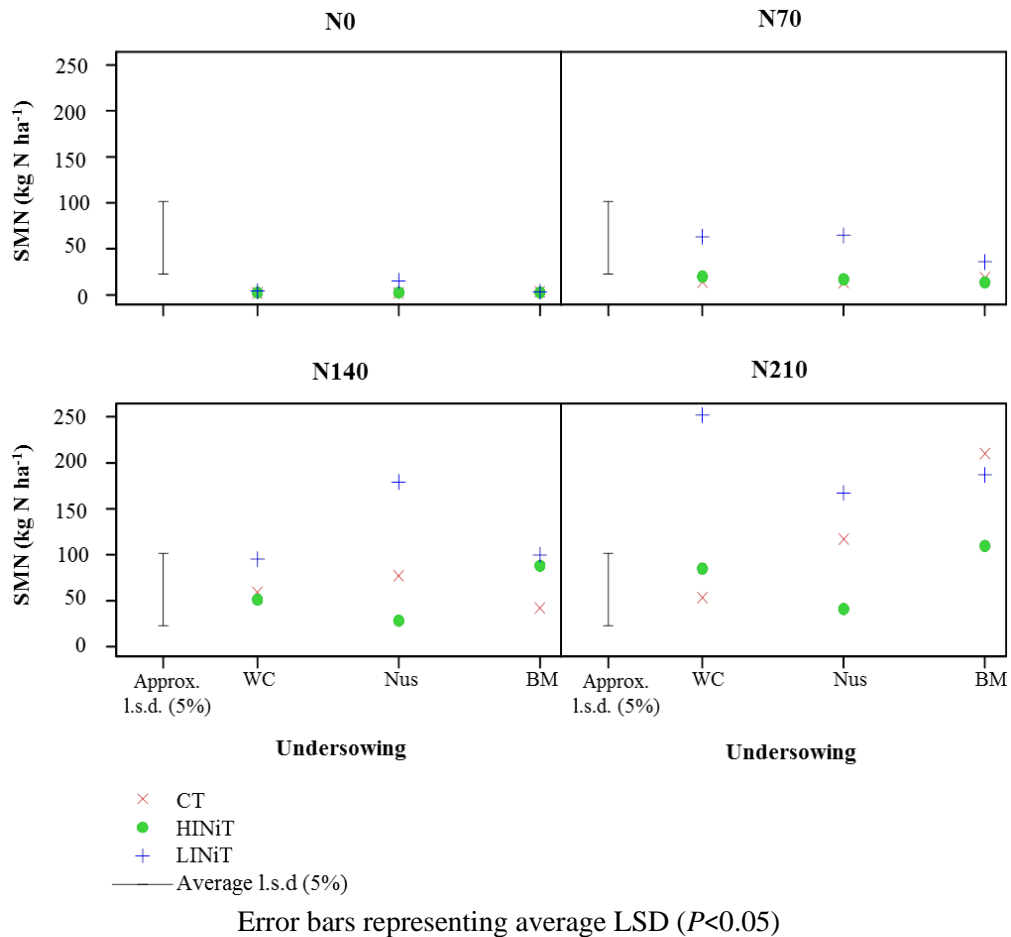
At the July assessment, under WC, the highest SMN content was obtained with N210. Under BM and Nus, the highest SMN was with either when N210 or N140 were applied (Figure 4.26).

Figure 4. 26. Effect of nitrogen fertilisation and undersowing interaction on soil mineral nitrogen (kg N ha⁻¹) (July 2013)

Error bars representing average LSD (*P*<0.05)
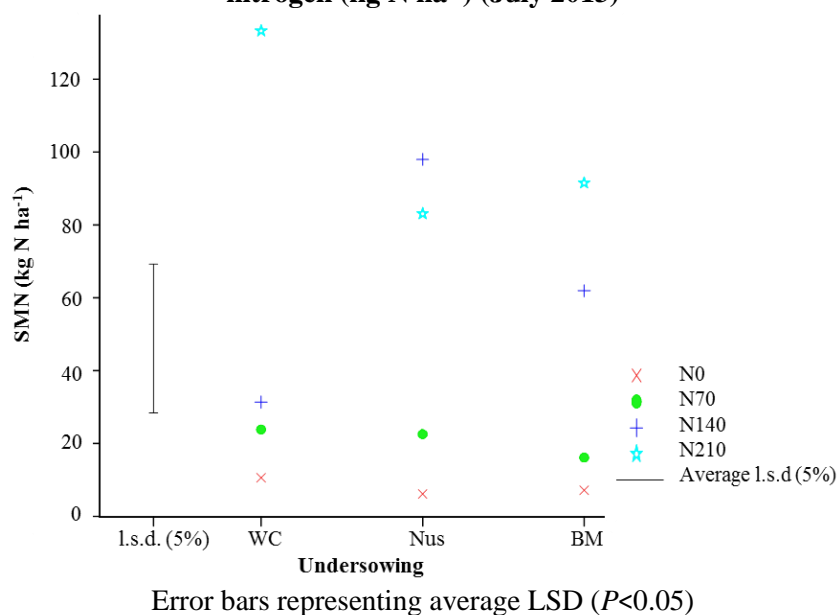
The relationship between SMN content and wheat N uptake at mid-season growth assessments and harvest time among treatments are plotted in Figure 4.27 and 4.28.

Figure 4. 27. Soil mineral nitrogen and wheat N uptake in 2013 season (kg N ha⁻¹) under three cultivation techniques

	March	April	May	June	July	August
SMN (LSD)	5.51^{ns}	5.84^{ns}	9.31***	67.70^{ns}	38.16^{ns}	26.90^{ns}
Wheat N uptake (LSD)	-	-	4.20**	-	31.28^{ns}	16.99*
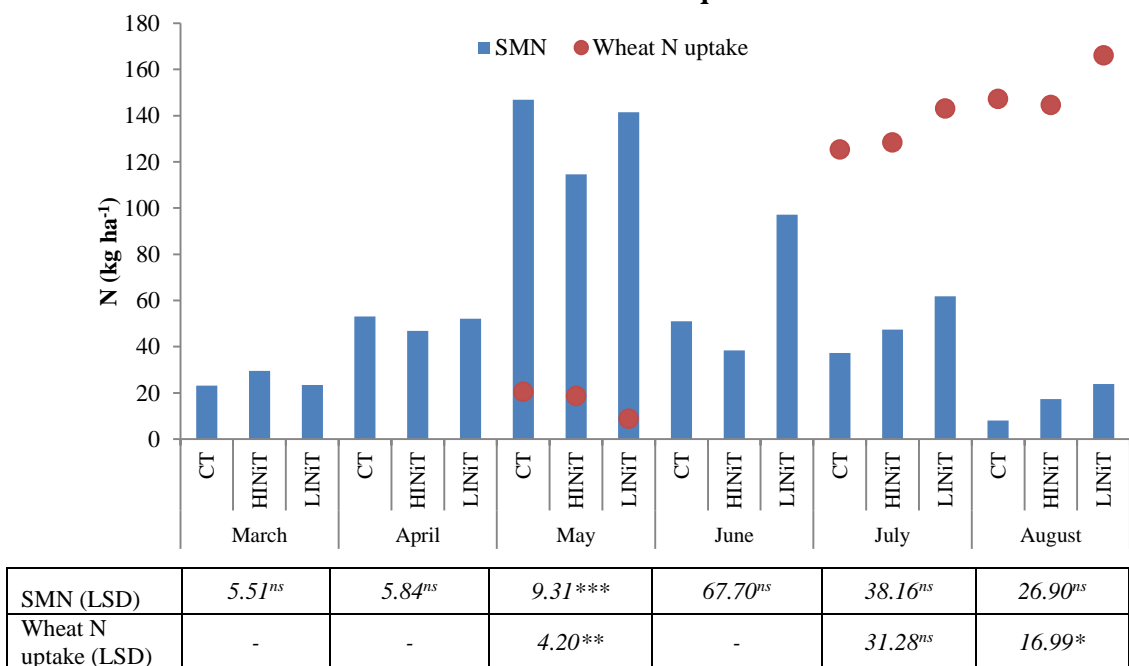
LSD at *P*<0.05 at each month of assessment; *= *P*<0.05; **= *P*<0.01, ***= *P*<0.001; and *ns*= no significant

Figure 4. 28. Soil mineral nitrogen and wheat N uptake in 2013 season (kg N ha⁻¹) under four nitrogen fertilisation rates
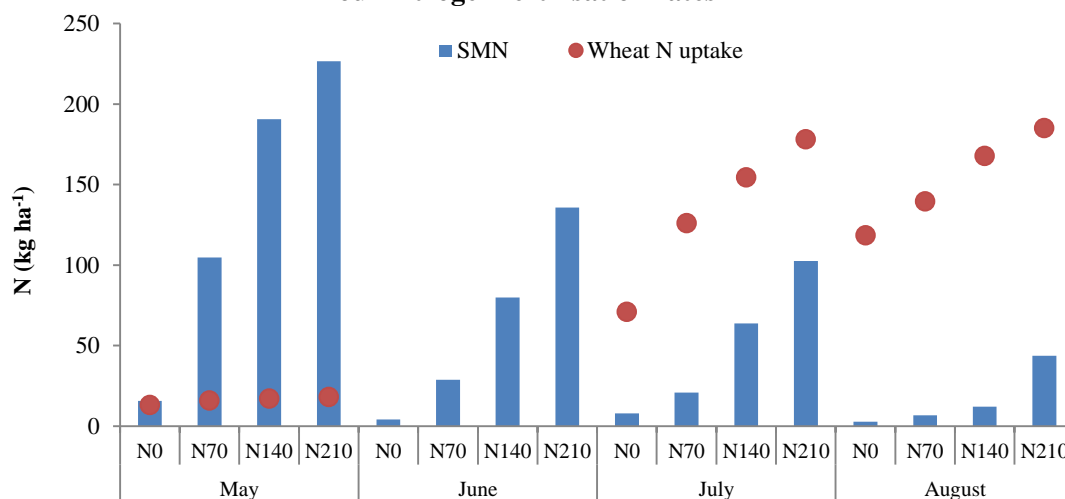
	May	June	July	August
SMN (LSD)	*30.81****	*38.39****	*29.02****	*16.82****
Wheat N uptake (LSD)	*2.27***	-	*23.35****	*28.41****

LSD at *P*<0.05 at each month of assessment; **= *P*<0.01 and ***= *P*<0.001

4.3.11. Soil moisture (gravimetric) content

Across assessments, the cultivation treatments influence on soil moisture content was variable with significant differences found only in March, July and August (Figure 4.29). In March, soil moisture content was significantly lower (*P*<0.01) under CT compared with HINiT and LINiT (Figure 31). In July, CT resulted in a significant (*P*<0.05) lower moisture content than HINiT, and LINiT. Furthermore, in August the moisture content was significantly lower (*P*<0.05) under CT than LINiT.

Variable soil moisture contents were observed across the cropping season under different N fertilisation treatments, except in August when no significant effect was observed (Figure 4.29). In May, the soil moisture was higher when under N70, compared specifically with N140. In June, the N0 and N70 showed the highest soil moisture content. In July, the N210 presented significantly higher moisture content.

Throughout the assessments times, there were no significant effects of undersowing treatments, or any treatment interaction on soil moisture content.

Figure 4. 29. Effect of cultivation techniques and nitrogen fertiliser treatments on soil gravimetric moisture content (%) with mean precipitation during the 2013 experimental period in comparison to the 10-year average
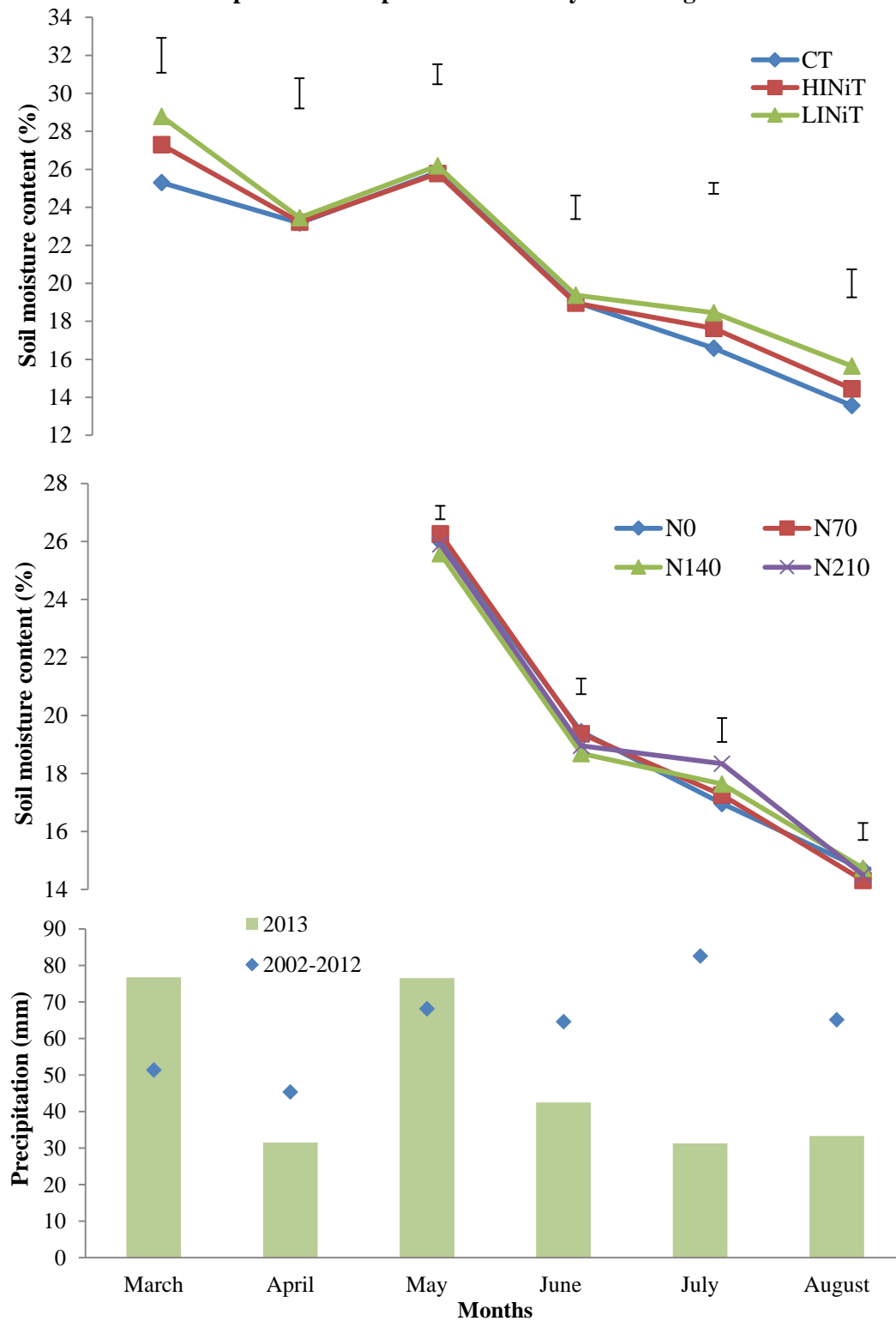
Error bars representing LSD ($P<0.05$) at each month of assessment

4.3.12. Soil pH

Irrespective of the management treatments and assessment times, soil pH was 7.02 (mean as a result of Repeated Measurements ANOVA). However, soil pH was only significantly affected ($P<0.01$) by N fertilisation at the June assessment with higher pH under unfertilised plots compared with fertilised ones, regardless of the N rate applied (Table 4.18). No significant effect of cultivation techniques, N fertilisation, undersowing or any treatment interaction was observed at any other assessment time.

Table 4. 18. Effect of nitrogen fertilisation on soil pH (June 2013)

	pH
N0	7.225b
N70	6.979a
N140	6.877a
N210	6.976a
SED (18 df)	*0.100*
P	**

Values followed by same letter, do not differ significantly at *P<0.05; **= P<0.01*

4.3.13. Soil penetration resistance

Before cultivation operations in February 2013, soil penetration resistance was evaluated in order to further test the previous year effect under contrasting tillage systems and to obtain initial values for the present study. Results showed a significant ($P<0.05$) cultivation techniques *x* soil depth interaction (Figure 4.30). At this assessment time, at 15 cm depth, CT resulted in lower soil penetration resistance compared specifically with LINiT. At 30 cm depth, HINiT resulted in lower penetration resistance compare with CT. Penetration resistance significantly increased ($P<0.001$) with depth, with 5 cm and 10 cm soil layers showing lower resistance than 15 cm and 30 cm soil layers.

Figure 4. 30. Effect of cultivation techniques and soil depth interaction on soil penetration resistance (kPa) (February 2013) with cultivation techniques soil disturbance depth

Error bar represents average LSD value at *P*<0.05
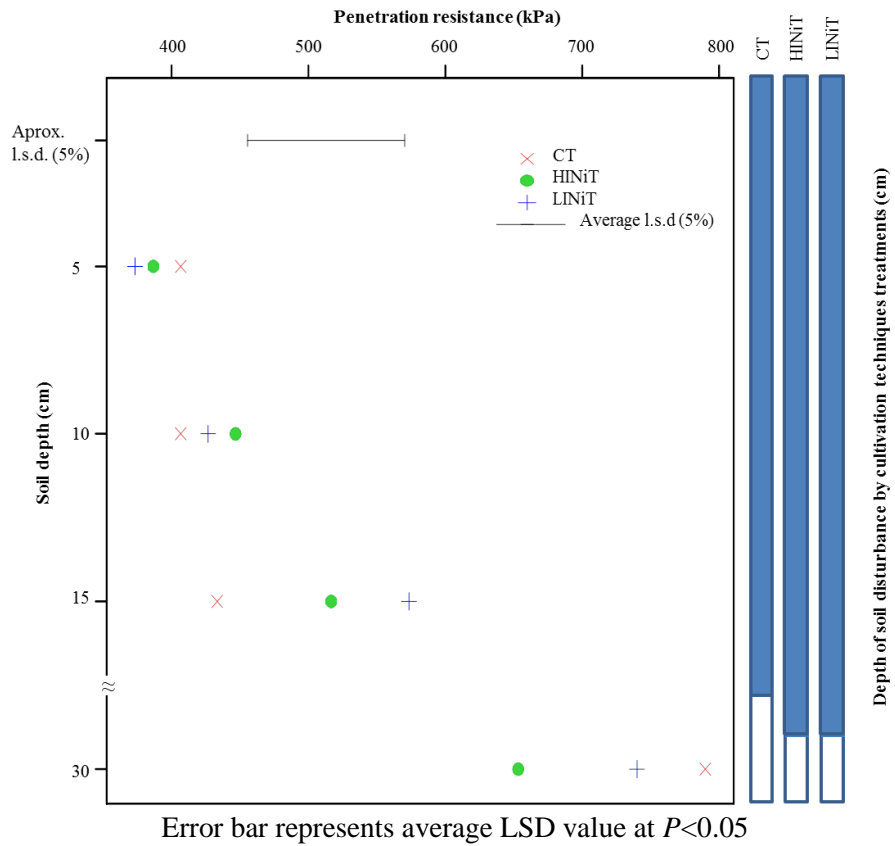
After cultivation operations (April 2013), at any assessment time, soil penetration resistance was not significantly affected by cultivation techniques treatments. The mean values were therefore reported in Figure 4.31. However, at 30 cm depth significantly higher (*P*<0.001) penetration resistance was found compared with any above soil layer.

Figure 4. 31. Effect of cultivation techniques and soil depth interaction on soil penetration resistance (kPa) (mean values 2013) with cultivation techniques soil disturbance depth

Error bar represents average LSD value at *P*<0.05
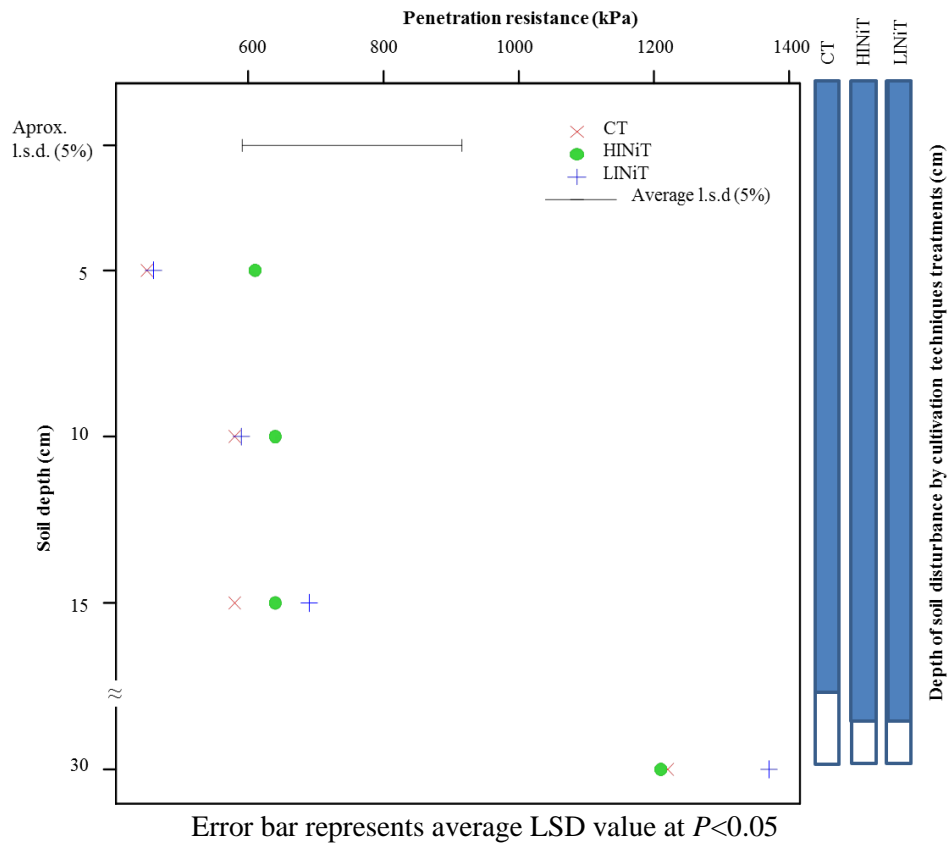
4.4. Discussion

4.4.1. Plant establishment, tillers and total shoots number

Cultivation techniques effect

Overall plant establishment was 77% of the seed sown (480 seeds m^{-2}), regardless of the management treatments. Plant establishment and early crop growth were affected by modifications of the seedbed conditions created by cultivation techniques operations, as reported by Strudley *et al*. (2008). The greater soil disturbance generated by CT in this clay soil created a level and even seedbed and incorporated plant residues into the soil. This allowed better seed-soil contact resulting in significantly greater plant establishment. More limited soil disturbance and greater plant residues cover on the soil surface under non-inversion tillage systems produced a coarser and highly variable seedbed conditions resulting in lower plant establishment, as also reported by other

studies (Känkänen *et al.,* 2011; Pietola & Tanni, 2003; Rieger *et al*., 2008). Maximum reduction of soil disturbance and greater presence of residues under LINiT resulted in lower plant density compared with HINiT and CT. The presence of plant residues on the soil surface can also interfere with drill operations causing an uneven seedling depth and seed-soil contact under non-inversion tillage, as others report (Siemens *et al.*, 2004; Wilkins *et al*., 1989). Additionally, high plant residues soil cover, particularly wheat straw, under non-inversion tillage treatments can release phytotoxic substances negatively affecting crop establishment and growth, as widely reported (Alam, 1990; Elliot *et al*., 1976; Lovett & Jessop, 1982; Rice, 1984).

Variations of the seedbed conditions that affected plant establishment also appeared to affect wheat tillers production. Differences in tiller number per unit area between HINiT and CT were not as large as those observed for plant establishment, as also reported by Wade *et al*. (2006). Plants under HINiT compensated for lower plant density, at least partially, by tillering. Maximum reduction of tillage intensity and greater soil residues cover, under LINiT, can slow soil warming and drying resulting in a cold soil environment (Børrensen & Njos, 1990; Shinners *et al.,* 1994), and consequently affected tillers production and shoot number. Better soil conditions under CT increased plant number and increased the early performance of the crop, represented by increasing tillers and total shoot number.

Nitrogen fertilisation effect

Tiller formation and total shoots were positively correlated with N supply as also reported by Power & Alessi (1978) and Rieger *et al*. (2008). An increasing number of tillers were produced by increasing N rate up to 210 kg N ha^{-1} and resulting in larger number of shoots, like reported by Weisz *et al.* (2001). N application at the wheat tillering stage has provided additional N to the crop promoting additional tiller development, as reported by other authors (Otteson *et al.,* 2008; Power & Alessi, 1978; Sarandon & Gianibelli, 1990; Weisz *et al.*, 2001).

Interaction effect

Even though N fertilisation rates did not significantly affect crop establishment, CT resulted in greater number of plants per unit area when 140 kg N ha^{-1} was applied. This

suggests N application could have encouraged a more rapid and stronger seedling growth promoting final establishment (Power & Alessi, 1978). Less soil movement intensity without inversion and the higher presence of plant residue cover under LINiT possibly resulted in initial N-immobilisation. Applying up to 210 kg N ha^{-1} supported more plants establishment, therefore, and also increased shoot production under LINiT. HINiT appears to increase N availability reducing the need for extra N supply, as greater shoot number was observed with up to 70 kg N ha^{-1}. Nevertheless, maximum tillage intensity by soil inversion under CT resulted in a higher number of shoots when N was applied up to 140 kg N ha^{-1} suggesting N fertilisation also encouraged higher tillers survival. This was also observed by Ottenson *et al.* (2008) reporting that shoots numbers can be increased with N fertiliser.

4.4.2. Mid-season plant biomass and nitrogen uptake

4.4.2.1.Wheat

Wheat biomass varied throughout the mid-season assessments among cultivation techniques and N fertilisation rates.

Cultivation techniques effect

Treatments that affected plant establishment and tiller production had a significant effect on wheat DM at the May assessment. Higher crop biomass production under CT seems to be related with greater plant population and tillers produced. Under HINiT, in spite of lower wheat establishment compared with CT, it seems that compensatory effect of tillering may result on similar biomass compared with ploughed soils, as also reported by Rieger *et al*. (2008). Variations in seedbed conditions and high rainfall conditions observed in May resulted in slow initial wheat growth under LINiT, as Mehdi *et al.* (1999) report. The greater presence of plant residues under LINiT, could have reduced soil temperature in the top layers, as the seedbed remains moist for longer slowing wheat growth as suggested by Cannell (1985). Acharya & Sharma (1994) also reported that a reduction in tillage intensity increases seedbed variability, resulting in less mid-season cereal biomass compared with CT.

Total wheat N uptake was, to a large extent, determined by cultivation techniques that significantly affected crop growth and biomass accumulation, as also reported by Gastal & Lemaire (2002). Initial growth assessment showed that CT and HINiT had significantly greater wheat N uptake and, therefore, greater wheat biomass than LINiT.

In spite of the increasing number of shoots by increasing tillage intensity, wheat biomass at the July assessment seemed to be more affected by environmental conditions. The ability of the soil under contrasting tillage intensity to maintain moisture at times of low rainfall (in and before July) was more likely to create variations in wheat growth across assessments, as also reported by others (Mehdi *et al.,* 1999; Lafond *et al.*, 2006). Non-inversion tillage, and specifically LINiT improved soil moisture content during dry weather conditions, reducing wheat stress and supporting crop growth. This possibly compensated for poor early growth under non-inversion tillage, at least partially, as differences between cultivation techniques in wheat DM at the July assessment were not significant. It seems that early crop growth was most likely to be affected by an uneven seedbed condition affecting plant establishment, rather than moisture availability as observed later in the season.

Nitrogen fertilisation effect

N supply is widely reported to substantially increase crop biomass (Campbell *et al*., 1977; López-Bellido *et al*., 2005; Pearman *et al*., 1977). This was also observed in the present study throughout all growth assessments. Increases in wheat biomass before anthesis was mainly related by increases in tiller and shoot production, and by increasing leaf expansion, like also reported by Pearman *et al*. (1977) and Gastal & Lemaire (2002). In May, crop growth was slower and the canopy smaller, and its N rdemand was also expected to be low. Increasing N rates up to 70 kg N ha^{-1} seems to be enough to have increased wheat biomass at this stage. However, in July, crop canopy was bigger possibly leading to a higher N demand. This suggests that N uptake was based on the soil N availability to meet such high crop N demand, as also reported by Justes *et al*. (1994) and Power & Alessi (1978).

Interaction effect

During the first growth assessment, it seems that N availability was a limiting factor for the crop for early growth under LINiT, as higher wheat DM and N uptake was obtained with up to 210 kg N ha^{-1}. Reducing soil disturbance under LINiT possibly reduced plant-available N by immobilization, increasing the need for additional N supply in order to meet crop requirements, like also reported by Radford *et al*. (1992). Additionally in May decreases in N uptake under LINiT compared to HINiT and CT in all undersowing treatments were observed. This suggests a more relevant effect of the cultivation techniques on the crop N uptake than the undersowing.

4.4.2.2.Legumes

Establishment and biomass of undersown legume species were quite low throughout growth assessments. Before and until a week after legume broadcast, higher temperatures and absence of rainfall resulted in low soil moisture content which could possibly have affected germination, establishment and biomass production. It could be assumed that the lack of undersowing effects in a large range of treatment assessments was an indirect effect of low legume establishment rather than a direct effect of the undersowing *per se*.

Nitrogen effect

Legume persistence has often been reported incompatible with N fertilisation (Soussana & Arregui, 1995). Undersown species, *Trifolium repens* L. (WC) and *Medicago lupulina* L. (BM) exhibited smaller biomass, slow growth rate and increased leaf and root longevity resulting in poor competitive ability under N-rich conditions (Döring *et al.,* 2013). These patterns resulted in lower legume biomass at the July assessment under fertilised conditions, as also reported by Moss *et al*. (2004) and Döring *et al.* (2013). Additionally, N fertilisation can increase wheat competitiveness resulting in an indirect adverse effect on legume undersown (Gooding & Davies, 1997).

4.4.2.3.Weeds

Most of the weeds species identified are commonly report in spring wheat production (HGCA, 2010) and their presence was influenced by the agricultural managements adopted and time of assessment as reported by Menalled *et al.* (2001). Total weed biomass constituted between 8.1% and 16.9% of the total plant aboveground biomass at the May and July assessment, respectively.

Cultivation techniques effect

Grass weeds appear to be a major challenge for cereal production, specifically when non-inversion tillage systems are adopted (Vijaya Bhaskar *et al.*, 2014). To overcome this challenge, a broad spectrum pre-cultivation herbicide glyphosate was applied, irrespective of treatments. Although, the approach employed in this study for the herbicide application did not allow us to test its specific impact on weed dynamics, it is possible to speculate on its relative effect on weed occurrence. Some studies (e.g. Mavunganidze *et al.*, 2014) report that a broad-spectrum herbicide as glyphosate controls both grass and broadleaf weed species. However, in the present study it appears that by applying herbicide, grass weeds seemed to be restricted and were less relevant compared with broadleaf weed species, throughout all of the mid-season assessments, like also reported by Ewald & Aebischer (2000) and Marshall & Nowakowski (1996).

As grass weed species prevalence was low, broadleaf weed species mainly accounted for the differences between tillage treatments on the total weed DM. This was observed as HINiT resulted in higher total weed and broadleaf weeds DM than LINiT and CT. Others authors (e.g. Clements *et al.*, 1996a; Swanton *et al.*, 2000) reported lower broadleaf weed species under CT compared with non-inversion tillage practices, like observed in this study particularly with HINiT. Delayed sowing due to increased rainfall (March 2013) could have allowed the emergence, after herbicide application, of weeds retained in the soil under non-inversion tillage. This condition combined with increases in soil disturbance intensity is the possible reason for high biomass of short-lived annual broadleaf weeds under HINiT. Higher presence of soil residues cover under LINiT created shadowing, reducing germination of some broadleaf species after herbicide application, as reported by Teasdale *et al.* (1991). For CT, weeds that escaped foliar

contact herbicide are likely to grow but the subsequent soil inversion is thought to have reduced broadleaf weed presence. This situation also provides a head-start for the primary crop, such that it can effectively compete with later emerging weeds, as other studies (Mahn, 1984; Menalled *et al*., 2001; Wicks *et al*., 1988) reporting lower weed biomass under CT also in spite of herbicide-use.

Nitrogen fertilisation effect

Weed DM at the May assessment was not significantly affected by N fertilisation. This was probably a result of the N fertilisation promoting a good start to the crop increasing its competitiveness against weeds, as the crop biomass and N uptake were higher, like also reported by Moss *et al*. (2004) and Davis & Liebman (2001). However, later in the season (in July), total weed DM increase their response to N fertilisation and broadleaf species DM increased especially with 70 and 140 kg N ha^{-1} applications. This was also reported by several authors (Blackshaw *et al*., 2003; Jørnsgård *et al*., 1996; Małecka & Blecharczyk, 2008; Moss *et al*., 2004) suggesting the weed N response depends on their differential competitiveness to uptake N.

Interaction effect

At the July assessment, HINiT resulted in a greater total weed and broadleaved weeds biomass with either N70 or N140 rate. Such effect is perhaps related to the increase of *Stellaria media* L. biomass, as the major weed species recorded. The increase of *Stellaria media* under HINiT is probably the result of seed retention in the soil and to the subsequent soil disturbance. Additionally, *Stellaria media* seems to be able to grow and reproduce under N-rich conditions and severe competition (Moss *et al*., 2004). These traits make *Stellaria media* the major weed species in this study high N conditions and one of the commonest species of intensively grown cereals in the UK (Moss *et al*., 2004).

Non-inversion tillage effect on total grass weed DM was not evident. However, seedbed conditions under LINiT were more advantageous for *Lolium perenne* L. to grow. This grass specie is susceptible to soil disturbance and specifically mechanical soil inversion, as also reported by others (e.g. Froud-Williams *et al*., 1983b; Hakansson, 2003; Tuesca & Puricelli, 2007). Additionally, the fast growth behaviour of *Lolium perenne* requires

high N supply (Daepp *et al.,* 2001), resulting in greater biomass under fertilised conditions, which could explain its greater biomass under LINiT combined with high N applications.

BM interacted with HINiT resulting in greater *Avena fatua* biomass and BM *x* LINiT interaction increased *Lolium perenne* biomass. These two weed species contributed to 20% of the total weed DM. Suggesting their role, to a large extent, for the total weed DM increases under BM and WC interaction with non-inversion tillage treatments. Slow growth of the undersown legume species allowed weed species with faster growth to establish, such as *Lolium perenne*, *Avena fatua,* and *Stellaria media* under fertilised N conditions, as also reported by Moss *et al.* (2004). Whereas under Nus, N70 and N140 application there was increased weed biomass, confirming positive weeds growth response to N supply.

4.4.3. Plant height and ears number

Cultivation techniques effect

Plant height reflects prevailing growing conditions and is affected by several factors, such as crop variety, soil conditions, weather patterns, and also by agricultural management performed (Malhi *et al*., 2007). Overall, the 2013 cropping season underwent uncommon and contrasting weather conditions compared to the long-term seasonal average. It appears that cultivation techniques effects on the early crop performance were overshadowed, or compensated for, by dry weather later in the season. Greater crop residue cover, particularly under LINiT, appears to limit soil water loss (Martinez *et al*., 2008) possibly promoting later plant growth under lower rainfall conditions, as also reported by Radford *et al*. (1992) and Guy & Lauver (2007). This perhaps compensated for slow early crop growth resulting in statistically similar plant height between tillage systems, as also observed on wheat biomass later in the season.

Agricultural management effects on plant establishment, and tiller production and survival affected ear production per unit area in the present study, like also reported by Mc-Master *et al*. (1994). The reduction of tillage intensity and greater soil coverage

under LINiT created higher seedbed variability affecting shoot survival and resulting in fewer ears compared with CT and HINiT, as also reported by Boomsma *et al*. (2010).

Nitrogen fertilisation effect

N application promoted vigorous plant growth, as previously discussed, which seems to also result in taller plants compared with unfertilised conditions, agreeing with Liu *et al.* (2013) findings. No significant effect of N fertilisation on ear number has been related, in some cases elsewhere, to the incidence of diseases, particularly *Fusarium* spp. (Pearman *et al*., 1977; Rieger *et al*., 2008). However, in this study, *Fusarium* spp. was not observed. Consequently, it seems ear number may merely be an expression of greater competition for available resources between an increasing shoot number, under fertilised conditions, as also reported by Power & Alessi (1978) and Pearman *et al*., (1977).

4.4.4. Ears, straw and total wheat biomass

Cultivation techniques effect

Weather conditions greatly affect plant growth, specifically those developments occurring during the dry period observed at grain-filling stage. Initial crop growth and development was highly encouraged under CT with more favourable seedbed conditions and lower weeds occurrence compared to non-inversion tillage systems, as mentioned by Mehdi *et al*. (1999). However, the ability to save soil moisture under non-inversion tillage systems perhaps reduced the initial differences observed between tillage systems. This may have resulted in similar ear, straw and total wheat DM, agreeing with Sainju *et al.* (2012). Saving, or perhaps increasing, soil moisture may be vital for crop production specifically under contrasting weather patterns or in months with scarcity of precipitations (Hansen *et al.,* 2011).

Nitrogen fertilisation effect

One of the main effects of mineral N fertilisation is to increase the size and duration of cereal canopy growth (Gooding & Davies, 1997). This was evident as N applications

increased wheat DM since the early growth assessments, and continued to increase straw DM at harvest especially with 210 kg N ha^{-1} rate, agreeing with Pearman *et al.* (1977). It seems that the lack of N significant effect on ear production was also translated to the total ear DM. As ear biomass is mainly defined by grains number and their weight, it is also possible that the N fertilisation influence on TGW and grains per ear counteracted resulting in a similar ear DM. This agrees with López-Bellido *et al.* (2000) and Rasmussen *et al.* (1997) reporting that raising N rate increased grains per ear while decreasing seed weight.

4.4.5. TGW, grains per ear, final grain yield and harvest index

Cultivation techniques effect

Greater ear production under CT and HINiT possibly created more competition for resources, resulting in lower number of grains produced compared with LINiT. This agrees with Pollard *et al*., (1981) reporting that less grains at harvest under ploughed plots were a result of more ears competing for resources. Fewer ear numbers under LINiT resulted in more grains per ear.

Thousand grain weight (TGW) is reportedly to be genetically determined (Mogensen *et al.,* 1985). However, several authors agree that the expression of TGW seems to be influenced by the cropping environment (so called GxE interaction). Therefore under stress situations, grains often appeared smaller and with less weight (De Vita *et al*., 2007; López-Bellido *et al*., 1998). Treatments that resulted in higher grains number per ear could possibly have caused a shrinking effect of the grains, while lower grains number increased their weigh (López-Bellido *et al*., 1998). This may have resulted in compensation between cultivation treatments on TGW.

Final grain yield is mainly determined by number of ears per unit area, grains per ear and TGW (HGCA, 2008b). Each of these yield components are related to growing conditions at different growth stages, although, each of them can in some part compensate for developments at earlier phases (HGCA, 2008b), as previously

discussed. This also emphasises the difficulties of relating final grain yield to the individual yield components, as previously highlighted by Gooding & Davies (1997).

Final grain yield under LINiT was higher than HINiT, and statistically similar to that of CT. Higher number of grains under LINiT could possibly have made the final grain yield under this treatment comparable with that of CT. Moreover, grain yield was also related to the crop N uptake, with LINiT resulting in high total wheat N uptake and yield. This may perhaps have been due to the soil being wet and cool at the beginning of the cropping season, leading to N losses and possibly high immobilisation under LINiT. Later in the season, dry and warm conditions combined with high soil moisture availability under LINiT, leading to increased N mineralisation. This allowed more N available for the plant, supporting the final yield under LINiT. Such results were also observed by Fox & Bandel (1986) reporting that comparable yield under reduced tillage with CT is the result of differences in N availability. In contrast, the lower grains number per ear and wheat N uptake under HINiT resulted in a lower final grain yield. These observations clearly suggest that for the 2013 cropping season, N and moisture availability, and number of grains per ear, have largely determined differences between cultivation techniques treatments on the final yield, as suggested by other studies (Brennan *et al*., 2014; De Vita *et al*., 2007; Fox & Bandel, 1986; Hansen *et al*., 2011).

As reported by Zhang *et al*. (2012), the present study showed that wheat yield can be increased without increases in DM production if the number of grains increases. This was observed in the harvest index (HI), which is the ratio of aboveground DM partitioning to grain yield, which was higher under LINiT than HINiT, and statistically similar to that of CT.

Nitrogen fertilisation effect

Increasing N supply increased grains number mainly by promoting nutrient availability, as also reported by Alijani *et al*. (2012) and Ferrise *et al.* (2010). Additionally, the higher availability of N might perhaps have reduced floret mortality resulting in higher number of grain with increasing N fertilisation rates, as suggested by Ferrante *et al.,* (2010). However, increases in grains per ear by N application appear to promote shortening of the grains reducing their weight, presented as lower TGW, agreeing with

several authors (Campbell *et al.,* 1977; López-Bellido *et al*., 2000; Pearman *et al*., 1977; Rasmussen *et al*., 1997). Ferguson (1967) also suggested that grains per ear and TGW in practice are often negative, being influenced by intra and inter-plant competition for resources available.

Grain yield depends on ears number, grains per ear and TGW (Campbell *et al.,* 1977; HGCA, 2008b), and it seems these yield components compensated resulting in similar grain yield between N treatments. Additionally, wheat yield response to N fertilisation is also influenced by factors such as growing environment conditions, soil type and cultivar (López-Bellido *et al.,* 2012). In this study dry weather conditions and the high clay content of the soil could have generated a significant accumulation of N in the soil profile. This caused additional soil available N for the crop, perhaps, contributing to high yield under unfertilised conditions. A lack of wheat yield response to N fertiliser application occurring overall. Similarly, several authors also reported no response of crops to N fertiliser attributable to high reserve of SMN (Abad *et al*., 2005; Corbeels *et al*., 1998; Johnson & Mattern, 1987; Miao *et al.,* 2015; López-Bellido *et al*., 1996). Increases in straw DM by N applications seem to have not supported final grain yield, resulting in a lower HI with increasing N rates, as also reported by Borghi (2000) and Pearman *et al*. (1977).

4.4.6. Wheat N yield, grain protein and N efficiencies

Cultivation techniques effect

Higher soil moisture and N availability under LINiT appears to encourage later crop growth increasing grain N uptake compared with CT and HINiT, although this was not observed in total wheat N uptake, and as reported by Fox & Bandel (1986). N availability does not always increase total plant N uptake as the wheat ability to capture N depends on various factors, especially synchronisation of soil $N0_3^-$ with crop demand (Halvorson *et al.,* 2001; Liao *et al*., 2004).

Wheat grain protein is greatly dependent on genotype (Johnson *et al*., 1985; Stobard & Marshall, 1990) but it is also influenced by the predominant growing environment (Rao

et al., 1993). Generally, there is a negative relationship between grain protein and final grain yield, reportedly due to energy constrains and N dilution effects (Terman *et al*., 1996; McNeal *et al*., 1982; Loffler *et al*., 1985; Pearman *et al*., 1978). However, this study like Kramer (1979) and Johnson & Mattern (1987), showed that for the same phenotype, grain yield and protein correlation is not always negative. There was no evidence of dilution effect of N assimilated resulting from high grain yield under LINiT, as grain protein content was also higher under LINiT than CT, and by HINiT. This effect perhaps is related to the increased N availability under LINiT, as also reported by López-Bellido *et al*. (2001). Gao *et al*. (2012) also suggested that increases in grain protein content can be ascribed to an increase in soil N supply, due to improvements in soil moisture content.

Although tillage systems significantly affected SMN, it had no significant effect on the crop N-use efficiency (NUE), agreeing with Brennan *et al*. (2014) and Giacomini *et al*. (2010). NUE can be partitioned into N capture by roots (uptake efficiency, NUpE) and its conversion to grain by shoots (utilisation efficiency, NUtE) (Moll *et al.,* 1982). Novoa & Loomis (1981) defines NUtE as the physiological efficiency of the N-use as it is the grain yield divided by the total crop aboveground N at maturity. Among cultivation techniques, LINiT resulted in lower NUtE compared with CT and HINiT. However, there were no observed relation between the crop total N uptake and the NUtE as also reported by Barraclough *et al.* (2010).

Nitrogen fertilisation effect

An increase in total wheat N uptake was evident with the application of 140 and 210 kg N ha^{-1}. However, grain N uptake was highly affected by increases in N rate resulting, particularly in higher grain N under N210 when compared with unfertilised conditions. These increases in total wheat and grain N uptake were also reported by Campbell *et al*. (1977) and Pearman *et al*. (1977). High crop N uptake under N-rich conditions can indicate the amount of unused N fertiliser present in a rooting zone at the time of crop requirement (Campbell *et al.,* 1977). In the present study, high-level of SMN content and high N uptake under high N rates treatments was not translated to higher yields while it was in grain quality, as also reported by Barraclough *et al*. (2014).

Reportedly, grain protein content is modified by the growing conditions, including interactions between management, genotype and environment (Gooding & Davies, 1997; Graybosch *et al*., 1996; Zhu & Khan, 2001). In this study, grain protein content varied with N supplied with values from 10% in unfertilised treatment to 14% with 210 kg N ha^{-1} applied. Similar results were also reported by other authors (Garrido-Lestache *et al.,* 2004; Godfrey *et al*., 2010; López-Bellido *et al*., 2001; Wieser & Seilmeier, 1998). Although, the highest grain protein was obtained with up to 210 kg N ha^{-1}, grain yield stayed unchanged by increasing N suggesting that higher N supply is needed in order to optimise grain protein rather than to maximise grain yield. This was also observed by Barraclough *et al*. (2014) evaluating several wheat varieties, including spring wheat cv Paragon in the UK, in reporting no correlation between grain yield and protein content at a given-N rate.

Crop N-efficiency parameters, NUE, NUpE, NUtE and NHI decreased under N fertiliser treatments. These results are mainly due to increases in aboveground N relative to grain yield reducing efficiency in the use of N, as also reported by Huggins & Pan (1993). Unfertilised treatment resulted in 52% higher NUE than the mean value for the N application treatments. This confirms that soil nitrate-N levels, under N0, were perhaps enough contribution to high grain yield as previously discussed and also reported by López-Bellido & López-Bellido (2001). Here, the low NUpE with increasing N rates can indicate higher available N than the crop demanded (Huggins & Pan, 2003). Furthermore, under high N rates, low NUtE and high protein suggest that once N is taken by the crop the physiological efficiencies decrease (Huggins *et al.,* 2010). Decrease in NHI under high N rates shows that high N uptake was not proportional to the final grain when increasing N supply. This agrees with López-Bellido & López-Bellido (2001), although it is contrary to Rozas *et al.* (1999) reporting greater N uptake resulted in greater yield thus increased NHI.

Undersowing effect

Low establishment and slow growth of the legume undersowed species resulted in a lack of significant differences between undersowing treatments, regardless of interactions, in almost every wheat development and production assessment, and in SMN and moisture content across the cropping season. However, NUE under Nus was

greater than with BM and similar to WC. However, cultivation techniques and N fertilisation exerted greater effects on N-efficiency parameters, making it more difficult to correlate such small undersowing effects on NUE.

4.4.7. Non-wheat biomass and N yield at harvest

4.4.7.1.Weeds

Application of broad-spectrum non-residual herbicide prior to cultivation operations appears to have reduced weed pressure regardless of the management treatments, as also reported by Derksen *et al*. (1995). However, weeds still occurred although their biomass seems to vary across the growing season. The dry weather conditions observed at the end of the cropping season and the enhancing wheat competition ability by increases in biomass, could have negatively affected weed development causing a decline in weed biomass at harvest (Jørnsgård *et al*., 1996; Mas & Verdú *et al.,* 2003). This was more marked on the major weed species, *Stellaria media* whose seeds germinate at or close to the soil surface making this species more susceptible to drought (Bond *et al*., 2007). Visual assessments corroborated weeds prevalence reduction during dry weather, affecting their biomass at harvest. Weed N uptake increased under fertilised treatments suggesting that weed N uptake was driven by differences in N supply, as also reported by Kamiji *et al*. (2014).

4.4.7.2.Legumes

Legume development patterns varied throughout the growing season. During mid-season growth assessments legume growth and development were poor, and do not appear to be related to any management treatment. However, at harvest time legume DM production increased, although still small reinforces that WC and BM have slower growth, as reported by other studies (Döring *et al*., 2013; Wallace, 2001).

Cultivation techniques effect

Higher variability and weed pressure under non-inversion tillage slowed legume growth, resulting in lower legume DM and N uptake than under CT at harvest time.

Nitrogen fertilisation effect

Legume DM and N uptake were reduced when N was applied compared to unfertilised conditions. This reinforces the negative relation between legume DM production under N-rich conditions as reported by several authors (Moss *et al*., 2004; Soussana & Arregui, 1995). N fertilisation effect on N uptake was related to legume DM production.

Interaction effect

Increasing tillage intensity favoured legume growth and N uptake under unfertilised conditions, possibly due to less variability of the seedbed and weed pressure under CT. Under unfertilised conditions, Nus resulted in higher N uptake compared with BM and WC species. Nus treatment was not completely free of legume probably due to some natural regeneration, by stolons (WC) and adventitious bud in roots (BM), in spite of pre-cultivation herbicide applications. Legumes were, therefore, separated from weeds even though they were legume weeds in these plots rather than deliberately undersown legumes. This could possibly have triggered differences on legume N uptake.

4.4.8. Soil moisture content

Soil moisture content followed a temporal pattern following rainfall events across the cropping season. This was particularly evident in March and May when rainfall and soil moisture content were higher followed by low moisture during summer months.

Cultivation techniques effect

In the present study, right after cultivation operations (in March 2013), increasing tillage intensity and soil inversion under CT reduced soil moisture. This was likely a consequence of breaking the soil water-related pores and increasing evaporation intensifying water loss (Reicosky *et al*., 1999). In contrast, less tillage intensity and

without soil inversion together with greater plant residues cover under LINiT and HINiT resulted in higher soil moisture content. These results agree with several studies (Fabrizzi *et al*., 2005; Fuentes *et al*., 2003; Hatfield *et al*., 2001; Lampurlanés *et al*., 2001) reporting greater soil moisture under non-inversion tillage. High moisture content under non-inversion tillage treatments is attributable to several factors such as more water-related pores (Bescansa *et al*., 2006). Additionally, plant residues protected the soil reducing evaporation and run-off, and in part decreasing soil temperature slowing soil drying, particularly at the surface (Baumhardt & Jones, 2002; Beyaert *et al*., 2002; Shinners *et al*., 1994). These conditions were particularly more evident in July and August when crop development had possibly dried the soil as increased transpiration, and limited rainfall occurred highlighting the soil's ability under LINiT to potentially save soil moisture content. This has also been reported by several authors (Baumhardt & Jones, 2002; Bescansa *et al*., 2006; Malhi *et al*., 2007; Singh *et al*., 1998).

The potential accumulation of soil moisture by non-inversion tillage systems during dry periods possibly encouraged wheat growth, and is most likely to be one of the possible explanations for the equivalent final grain yield between LINiT and CT. Since summers are expected to be drier in the UK as a result of climate change (Christensen & Christensen, 2007; Jenkins *et al.,* 2008, 2009) greater water availability observed under non-inversion tillage would seem to favour its use.

Nitrogen fertilisation effect

N fertilisation effect on plant growth towards maturity seems to indirectly affect soil moisture content from May to July. At this time, N supply promoted crop biomass production possibly increasing crop water uptake and reducing soil moisture levels. This agrees with Campbell et al. (1977) who reported a rise in plant water uptake under heavily N fertilised growing conditions. López-Bellido et al. (2007a) also related lower crop growth under unfertilised conditions resulting in higher soil moisture content levels. During crop production phase, specifically in July, higher soil moisture content was observed in the plots fertilised with high N rates. This was probably due to rapid biomass stimulation by N supply, covering the soil and reducing the surface susceptible to evaporation, and enhancing moisture storage, as also reported by several authors (Corbeels et al., 1998; Hatfield et al., 2001; López-Bellido et al., 2007b). This occurred

despite the dry weather conditions and that during crop production phase ample N and water uptake, and transpiration were expected (HGCA, 2008b). Despite the variable soil moisture response under different N treatments at each month of the growing season, it seems that there is a general pattern suggesting that increasing N fertilisation will promote higher crop biomass potentially reducing soil moisture content.

4.4.9. Soil mineral nitrogen

Cultivation techniques effect

Interactions between biological processes and solute transfer in the soil result in inorganic N dynamic, which is influenced by weather conditions, soil type and cropping system (Oorts *et al.,* 2007). In the present study, contrasting soil disturbance and plant residues soil cover left by the cultivation techniques affected soil N mineralisation, as reported by other studies (Myrbeck *et al*., 2012; López-Bellido & López-Bellido, 2001; Silgram & Shepherd, 1999). However, cultivation effects are often reported to be temporal and frequently to increase SMN content when increasing tillage intensity mainly by exposing organic matter to decomposition, as reported by Myrbeck *et al*. (2012) and Silgram & Shepherd (1999). In the present study no significant differences were observed after cultivation operations, however, as also reported by Fuentes *et al*. (2003) and Oorts *et al*. (2007). While no leaching measurements were conducted, it is suspected that lack of significant differences between tillage treatments after cultivations operations (March 2013) was related with high rainfall recorded at the end of March. This possibly increased the risk of leaching the N mineralised after cultivations operations, as reported by Oorts *et al*. (2007) comparing tillage systems in a clay textured soil.

Differences between cultivation techniques on SMN were then noticeable in May when higher levels of N was recorded compared with previous months following the N fertiliser applications. Plant N uptake is highly related to SMN levels (Brennan *et al*., 2014). Differences in plant establishment under tillage treatments led to variations in plant N uptake, possibly resulting in variation of the residual SMN left in the soil. Lower plant populations under LINiT resulted in less N uptake probably leaving higher

residual N in the soil, as reported by several authors (Brennan *et al*., 2014; Riley, 1998; Thomsen & Sørensen, 2006). On the contrary, despite increasing soil disturbance intensity under HINiT, higher plant number resulted in greater N uptake reducing SMN levels when compared specifically with LINiT. However, under CT, SMN level seems more related to a larger mineralisation rate at this time of the cropping season rather than being related with crop N uptake.

From June to August, towards wheat maturity, SMN level decreased when crop N uptake increased. These temporal variations of SMN were similar to those found by Fuentes *et al*. (2003) and Oorts *et al*. (2007) who reported that small seasonal differences in SMN between cultivation techniques were attributed to delayed N mineralisation. Conditions of low water availability limit soil microbiota slowing N mineralisation (Jenkinson *et al*., 1987; Rasmussen *et al*., 1998). Crop N uptake potentially depletes soil available N, therefore.

Nitrogen fertilisation effect

Application of mineral N fertiliser increased SMN levels, as also reported by other studies (Angás *et al*., 2006; Giacomini *et al*., 2010; Liebig *et al*., 2002; Lu *et al*., 2010; Zhao *et al*., 2014). However, SMN decreased rapidly as the cropping season progressed, mainly due to increases in crop N uptake as the crop approaches to maturity (Fuentes *et al*., 2003). The remaining soil N also depended on initial N levels (initial soil N plus N mineral fertilisation applied) and possible mineralisation. At initial crop growth stages, applying more N than the crop needed could lead to N accumulation in the soil (Angás *et al*., 2006). This was observed at the initial assessments months, when large SMN content was observed with 210 kg N ha^{-1} applied. While, under N0 and N70, a rapid depletion of SMN was observed across the experimental time due to higher plant uptake than the N supplied. This agrees with Zhao *et al*. (2014) who reported a low SMN content under low mineral N addition as the crop uptake was higher than the supply, whereas the opposite happened under N-rich conditions which exceeded crop uptake levels. Moreover, differences found between N rates treatments decreased with time as a result of a proportional balance between N supply and crop N consumption.

<u>Interaction effect</u>

Undersowing legume species, such as BM and WC, hav been recommended for reducing N leaching and for increasing soil available N, even before their biomass incorporation into the soil (Döring *et al*., 2013). These characteristics could possibly suggest a greater effect in SMN content, although this was only observed when undersowing interacted with other management treatments. At the June assessment, BM and WC increased SMN levels with N210 under LINiT compared with Nus, while under CT with N210, BM increased SMN compared to WC and Nus. SMN increases by legume undersown suggests, perhaps, a release of N by the legume species as reported by Bergkvist (2003). Känkänen *et al.* (2001) also reported increases in SMN when legumes were undersown under high levels of N fertilisation, compared with monocrops. However, this was not translated in greater crop N uptake contrary to results reported by Thorsted *et al*. (2006). Interactions between cultivation techniques and undersowing has also been reported to affect crop growth, biomass production, grain yield and weed population (Teasdale *et al*., 1991) affecting soil residual N, therefore, SMN levels. However, in the present study, cultivation techniques and N fertilisation showed a more marked effect making it more difficult to determine undersowing effect irrespectively of treatments interactions

4.4.10. Soil pH

Soil pH was found to be significantly affected by the N applications at the June assessment. This is possibly due to N fertiliser increased the anion H+ from the ammonium nitrification reducing soil pH (Magdoff *et al.,* 1997), as reported by Schroder *et al.* (2011) and Zhao *et al.* (2014). However, this effect of N fertilisation was only observed in June, suggesting that changes in pH are more highly influenced by environmental conditions and temporal variations as also reported by Spiegel *et al.* (2007). This perhaps also explain the lack of cultivation techniques effect on pH, contrary to Vijaya Bhaskar *et al.* (2013a) who reported higher soil pH under CT than reduced tillage systems.

4.4.11. Soil penetration resistance

Soil penetration resistance indicates how easily roots can penetrate the soil. High penetration resistance, therefore, can restrict root growth affecting crop production (Gregory, 1994). In the present study, penetration resistance at all soil depth layers was lower than 2MPa, which is the upper limit for uninterrupted root growth (Atwell, 1993). Before cultivation techniques operations, soil penetration resistance showed a depth gradient with increasing resistance from top soil layers (0 to 10 cm) to 15cm and then 30cm depth (despite soil moisture content not being directly assessed at different soil depths), as reported by several studies (Bradford, 1986; Campbell & O'Sullivan, 1991; Grant & Lafond, 1993; Martinez *et al.,* 2008). At this assessment time, the cultivation effects on penetration resistance indicate the legacy of the tillage operation previously used. At 5cm and 10cm soil layer, no significant differences were observed between tillage treatments suggesting a diminished effect of contrasting tillage treatment effect after a year from the initial operations, as also reported by Martinez *et al*. (2008). However, at 15cm soil layer, LINiT resulted in higher penetration resistance than CT. This is possibly the result of more intense soil movement created by CT equipment reducing soil compaction, compared with reduced tillage intensity under LINiT. Similar observations were also reported by Martinez *et al*. (2008) and Ozpinar & Çay (2005). Furthermore, soil inversion by ploughs increased soil compaction below plough-working depth (approx. 20 cm) increasing penetration resistance at 30 cm, compared specifically with HINiT, as also reported by Ardvisson *et al.* (2013). Nevertheless, significant differences between contrasting cultivation operations were reduced after their performance in March 2013. Across the 2013 growing season, penetration resistance was only related with depth resulting in lower resistance at top soil layers depth (0 -15cm) compared to 30cm, as observed by Grant & Lafond, (1993).

4.5.Conclusions

Key findings for the initial investigation on cultivation techniques are listed in Table 4.19. Initial investigation with spring wheat revealed the importance of seedbed conditions created by contrasting cultivation techniques in determining plant

establishment, growth and development. The success among cultivation techniques was initially demonstrated on plant establishment, and finally by reductions of negative effects under dry summer conditions.

Table 4. 19. Key outcomes for the cultivation techniques effects during 2013 cropping season

	CT	HINiT	LINiT
Tillage intensity	High	Intermediate	Low
Seedbed	Fine	Coarser	Much coarser
Seedbed evenness	Level / uniform	Variable / Not uniform	Highly variable / Not uniform
Plant establishment	High	Intermediate	Low
Tiller production	High	High	Low
Plant height	Statistically not significant		
Ears number	High	High	Low
TGW	Statistically not significant		
Number of grains per ear	Low	Low	High
Grain yield	[1]Comparable	Low	High
SMN	Low	Low	High
Moisture content	Low	Intermediate	High

[1]Statistically comparable with LINiT and HINiT

The potential initial plant establishment and higher number of tillers under CT were overshadowed by competitive and compensatory effects occurring on ear number and grains per ear, but this did not reduce final yield. However, less soil tillage intensity and greater plant residues cover under LINiT resulted in greater seedbed variability causing a slow early crop growth and less plant establishment than CT and HINiT. Nevertheless, greater soil moisture content and soil N availability under LINiT encouraged later crop growth, inducing greater grain number per ear and resulting on comparable yield with CT. In spite of initial cultivation influences on weed DM at mid-season assessments, no-significant differences were observed by harvest time. This was the result of

vigorous crop growth possibly competing against weeds and also the prevalent dry weather conditions inducing natural decay of the weeds.

Consequently, under this study soil and weather conditions, CT performance was constant from high crop establishment until final yield. On the basis of yield, LINiT seems, however, to be an acceptable alternative to CT. This agrees with other authors reporting equivalent performance of non-inversion tillage compared with CT, under deficient rainfall conditions during the cropping season (Brennan *et al.,* 2014; De Vita *et al.,* 2007; López-Bellido *et al*., 1996). The present study was encouraging, therefore, for the adoption of non-inversion tillage system as LINiT, for spring wheat production. However, with weather uncertainty further experimental study was necessary.

Regarding N fertilisation, key findings from the initial investigation are listed in Table 4.20. N fertilisation encouraged crop growth compared with unfertilised conditions. However, those differences between N rates were diminished, with no effects of N fertilisation treatment on final grain yield, mainly as a result of prevailing dry conditions and crop compensatory effects. Higher grain numbers by increasing N fertilisation supply was not supported at harvest, resulting in lower TGW creating a compensation effect and eclipsing N fertilisation influence on yield. SMN level in the soil under unfertilised condition appeared to be enough to encourage high yields as yields were similar than with N fertilised plots. In addition, N fertilisation also encouraged weed growth, increasing its biomass production although this seems to have not affected final wheat yield. In this study soil and prevalent weather conditions N fertilisation did not encourage yield gains, although further study is needed.

The scarcity of rainfall right after undersowing legume species were broadcasted resulted in poor establishment and slow growth, causing overall failure of the undersowing treatments. Even though some effects were observed, cultivation techniques and N fertilisation treatments effects were more evident making it more difficult to observe undersowing effects alone. Therefore, undersowing legume effects need to be investigated further to confirm that environment conditions in this season played a more relevant role than the undersown treatments *per se*.

Table 4. 20. Key outcomes for the nitrogen fertilisation effects during 2013 cropping season

	N0	N70	N140	N210
Tiller production	Low	[1]Comparable	[2]Comparable	High
Plant height	Low	Medium	[3]Comparable	High
Ears number	Statistically not significant			
TGW	High	Medium	Medium	Low
Number of grains per ear	Low	High	High	High
Grain yield	Statistically not significant			
SMN	Highly low	Low	Medium	High

[1]Statistically comparable with N0 and N140; [2]Statistically comparable with N70 and N210; [3]Statistically comparable with N70 and N210.

CHAPTER FIVE

Core experiment II - spring wheat 2014

5.1.Introduction

After spring wheat harvest on 28 August 2013, the soil was left with legume cover during the winter months and before drilling 2014 spring wheat. Soil cover was a combination of wheat straw, black medic, white clover and weeds (Plate 5.1). Due to the legume species ability to continue to grow after 2013 harvest, it was thought they could perhaps function as a catch crop accumulating N and limiting losses by de-nitrification (Döring *et al*., 2013; Jones, 1992; Jensen, 1991). In addition, the legume species might develop a dense canopy which could potentially assist with controlling weed establishment and growth (Breland, 1996; Clements & Donaldson, 1997). The experiment was, therefore, repeated with spring wheat cv Paragon to reinforce the 2013 crop performance findings.

Plate 5. 1. Overwinter soil cover

5.2. Materials and methods

5.2.1. Experimental site

The field experiment was conducted at the Royal Agricultural University's Harnhill' Manor Farm, Cirencester, UK, (NGR SP 075 006). Before cultivation techniques operations in 2014, 2 l ha^{-1} of a non-selective contact herbicide, a.i. glyphosate (Round-up), was applied throughout the experimental field.

5.2.2. Experimental design and treatment structure

The study was conducted from March 2014 to August 2014 on a field previously cropped with spring wheat cv Paragon. The experimental design and treatment structure were as previously described in Chapter 3, Material and Methods, § 3.1. The 2014 dates of each field operation are described in Table 5.1.

Table 5. 1. Diary of 2014 field operations

Field operation	Approximate date
Herbicide application	11 March 2014
Land preparation	24 March 2014
Spring wheat sowing	18 April 2014
Nitrogen applications	10 May / 30 May 2014
Undersowing	14 May 2014
Harvest	31 August 2014

5.2.3. Meteorological conditions

During the 2014 cropping season, maximum and minimum air temperatures were recorded in July (18.0 °C) and March (7.18 °C). Maximum and minimum rainfalls were recorded in May (97.3 mm) and March (39.5 mm). The 2014 growing season experienced lower air temperatures and the spring period experienced higher rainfall

conditions while rainfall in summer was lower compared to the long-term seasonal average (Figure 5.1).

Figure 5. 1. Mean air temperatures and precipitation during 2014 experimental period in comparison with the 10-year average. Royal Agricultural University meteorological station (NGR SP 42 004 011)

	March	April	May	June	July	August
2014	7.18	9.79	12.08	15.36	18.03	14.74
2002-2012	7.48	10.28	13.05	16.34	18.27	18.43

	March	April	May	June	July	August
2014	39.50	65.90	97.30	49.70	56.60	91.50
2002-2012	51.39	45.37	68.15	64.60	82.57	65.15
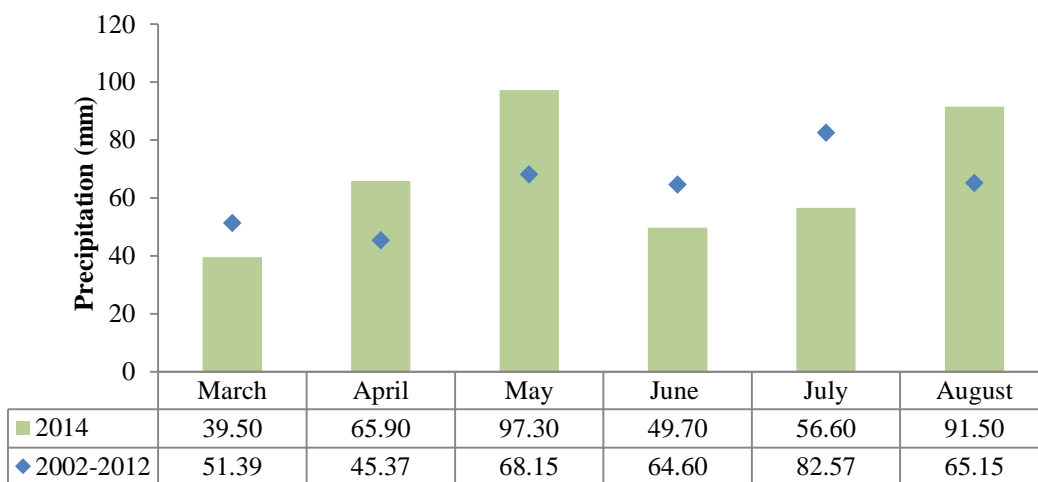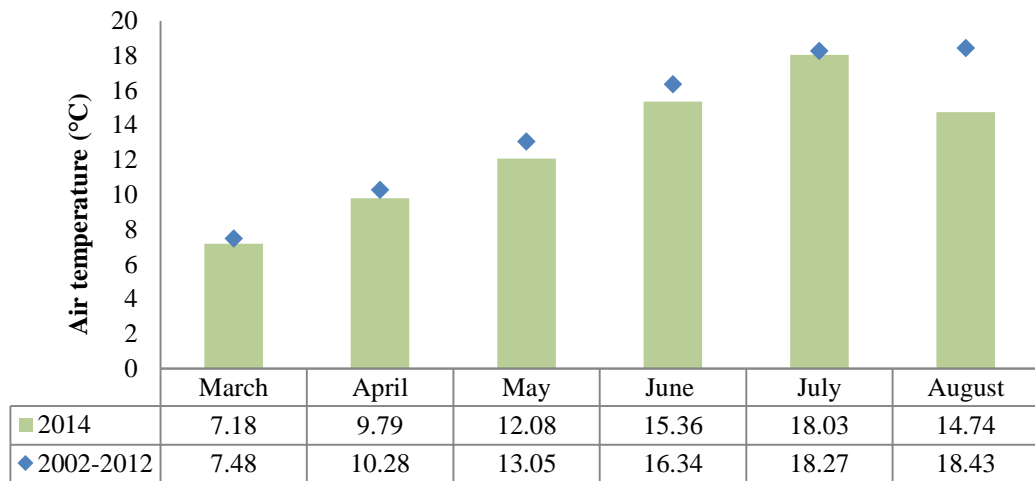
5.2.4. Assessments

5.2.4.1.Above ground assessments

Above ground assessments were previously described in Chapter 3, Material and Methods, § 3.3. Further details are presented in Table 5.2.

Table 5. 2. Above ground assessments for spring wheat 2014

Assessments	Approximate date
Overwinter legumes and weeds biomass	28 February 2014
Wheat establishment	07 May 2014
Wheat tillers number	28 May 2014
Wheat shoot numbers	16 June 2014
Growth assessments (wheat, weeds and legumes – BM and WC – biomass)	28 May 2014 / 01 July 2014 / 01 August 2014
Plant height	28 July 2014
Wheat ears number	28 July 2014
Diseases assessment	29 July 2014
Biological harvest	31 August 2014

5.2.4.2.Soil assessments

Soil assessments were previously described in Chapter 3, Material and Methods, § 3.4. Further details of the assessment dates are given in Table 5.3.

Table 5. 3. Soil assessments for spring wheat 2014

Assessments	Approximate date
Soil mineral nitrogen and moisture (gravimetric) content	Monthly. March 2014 – August 2014
Soil pH	March 2014
Penetration resistance	March, June and August 2014

5.2.5. Statistical analysis

Statistical analysis and reporting results are as previously described in Chapter 3, Material and Methods, §3.5. The severity of diseases was transformed using log-normal transformation $(\log(x!))$ $(x + 1$; x= percentage of leave infected) in Genstat (15th Edition VSN International Ltd, Hemel Hempstead, UK), to reduce heterogeneity of variance.

5.3. Results

5.3.1. Overwinter growth assessment

Overwinter assessments showed significantly higher ($P<0.01$) weed biomass and N uptake under LINiT than CT and HINiT (Table 5.4). N fertilisation significantly affected ($P<0.001$) weed DM, resulting in higher weed DM with N140 and N210 than with N0 and N70, while increasing N rate significantly increased ($P<0.001$) weed N uptake.

Legume overwinter biomass was significantly higher ($P<0.001$) under CT than HINiT, followed by LINiT, while legume N uptake was significantly higher ($P<0.01$) under CT compared with HINiT and LINiT (Table 5.4). N fertilisation treatments significantly decreased ($P<0.001$) legume DM and N uptake when compared with N0.

There was no significant effects of undersowing on overwinter weed and legume DM and N uptake.

Table 5. 4. Weed and legume biomass and N uptake (Overwinter 2013)

	Total weed DM (t ha^{-1})	Total weed N uptake (kg N ha^{-1})	Legume DM (t ha^{-1})	Legume N uptake (kg N ha^{-1})
CT	0.242a	5.66a	0.4568c	13.948b
HINiT	0.403a	10.48a	0.1485b	4.925a
LINiT	0.905b	23.11b	0.0614a	1.999a
SED (4 df)	*0.070*	*1.853*	*0.030*	*1.554*
P	**	**	***	**
N0	0.377a	7.43a	0.6546b	20.647b
N70	0.463a	10.76b	0.1232a	3.714a
N140	0.575b	14.41c	0.0556a	1.878a
N210	0.650b	19.73d	0.0556a	1.626a
SED (18 df)	*0.046*	*1.203*	*0.059*	*1.22*
P	***	***	***	***

Values followed by same letter, do not differ significantly at *P<0.05; **= P<0.01; ***=P<0.001*

Due to significant interactions, CT and HINiT resulted in significantly higher weed N uptake with N210, compared specifically with N0, while LINiT increased weed N uptake with increasing N rate (Figure 5.2).

Figure 5. 2. Cultivation techniques and nitrogen fertilisation interaction effect on overwintering weed N uptake
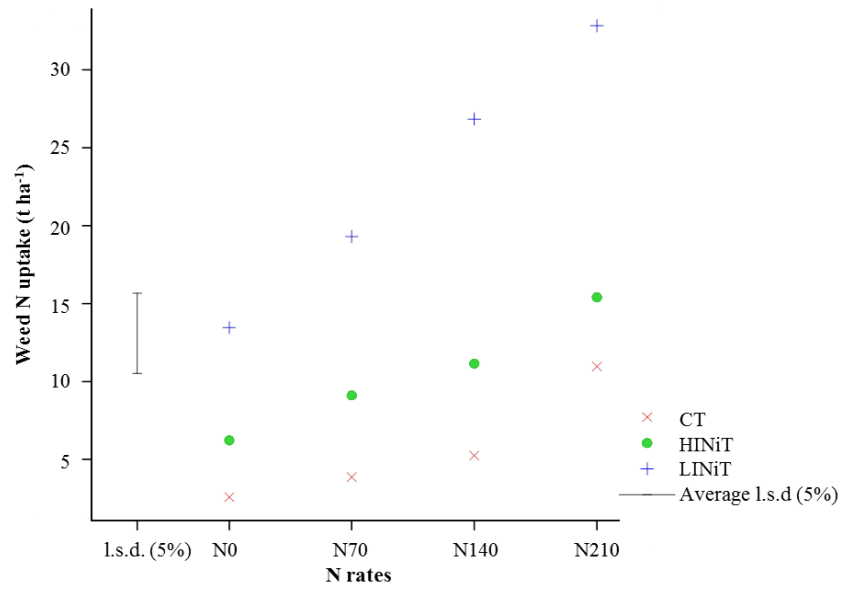
Error bars representing average LSD (*P*<0.05)

In addition, due to significant treatments interaction, under the Nus and WC regimes, with N70 and N140, LINiT resulted in higher weed N uptake compared with HINiT and CT (Figure 5.3). LINiT and HINiT resulted in higher weed N uptake than CT with N0 and BM, while with N140 and BM, the LINiT increased weed N uptake compared with HINiT and CT.

Figure 5. 3. Cultivation techniques, nitrogen fertilisation and undersowing interaction effect on overwintering weed N uptake

Error bars representing average LSD (*P*<0.05)

CT resulted in higher legume DM and N uptake compared with HINiT and LINiT under N0. Higher legume DM and N uptake were found with N70 under CT than HINiT and LINiT (Figure 5.4 & 5.5).

Figure 5. 4. Cultivation techniques and nitrogen fertilisation effect on overwinter legume biomass

Error bars representing average LSD (*P*<0.05)
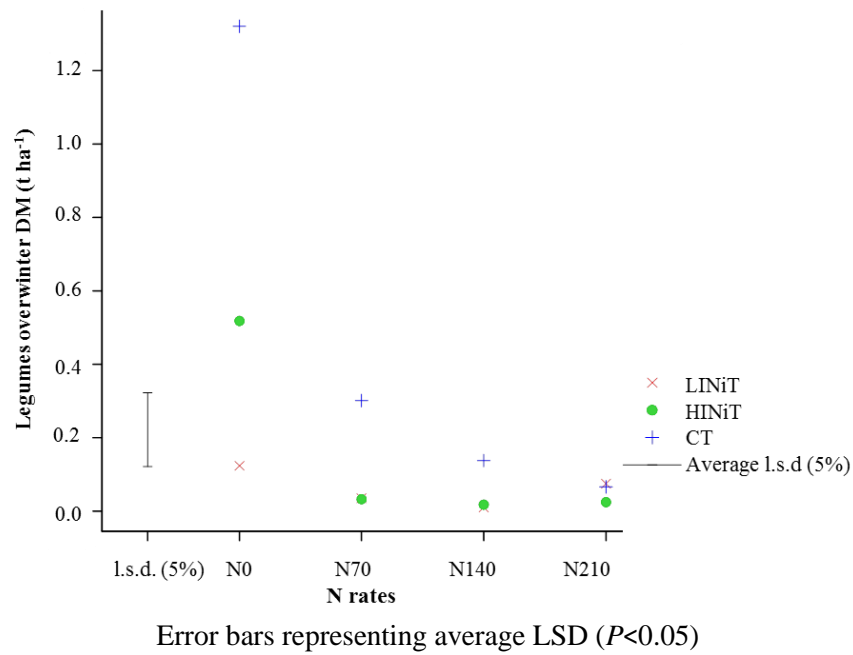
Figure 5. 5. Cultivation techniques and nitrogen fertilisation effect on overwinter legume N uptake

Error bars representing average LSD (*P*<0.05)
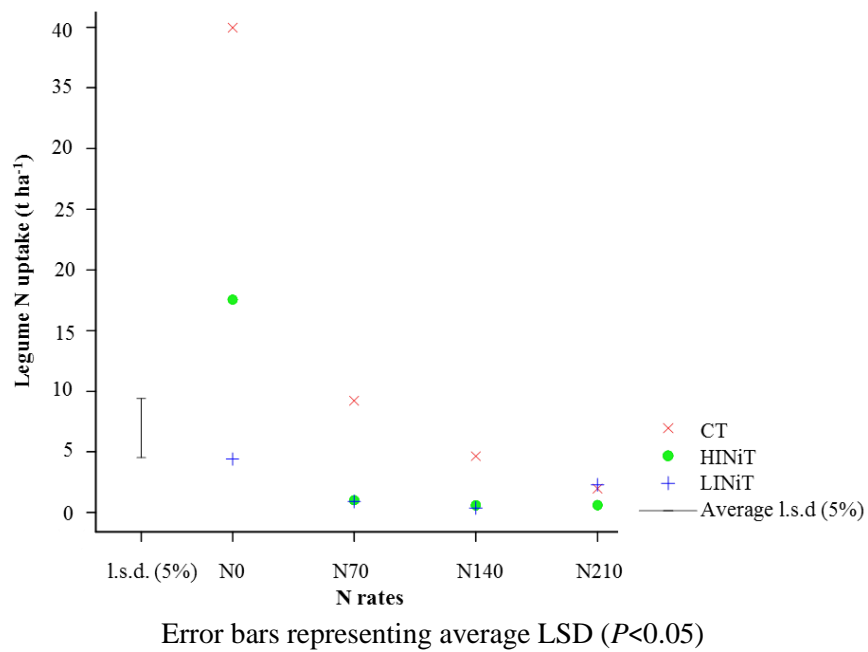
5.3.2. Plant establishment, tiller numbers and total shoots

In the present study, overall plant establishment was 52% of the seed sown, which was lower compared with spring wheat in 2013 (77%). Between the cultivation techniques, there was significantly higher plant establishment ($P<0.05$) under CT (62.5%) and HINiT (56%) compared with LINiT (37.3%) (Table 5.5).

Tiller production per unit area was significantly higher ($P<0.01$) under CT and HINiT than LINiT (Table 5.5). However, HINiT and LINiT resulted in significant lower ($P<0.01$) total shoot number compared with CT.

There were no significant effects of N fertilisation, undersowing or any treatments interactions on plant establishment, tillers number and total shoots.

Table 5. 5. Effect of cultivation techniques on establishment, tiller number and total shoot of spring wheat

	Establishment (number m^{-2})	Tillers (number m^{-2})	Shoots (number m^{-2})
CT	300.00b	508.80b	469.20b
HINiT	269.00b	471.90b	406.80a
LINiT	179.00a	400.60a	382.60a
SED (4 df)	*30.06*	*15.66*	*9.47*
P	*	**	**

Values followed by same letter, do not differ significantly at *P<0.05; *= P<0.05*, and
**=P<0.01*

5.3.3. Mid-season wheat biomass and nitrogen uptake

At the May assessment, CT resulted in a significant higher ($P<0.001$) wheat DM and total wheat N uptake compared with HINiT, followed by LINiT (Table 5.6). N fertilisation did not have significant effects on wheat DM, although N210 resulted in significantly higher ($P<0.05$) total wheat N uptake compared with any other N rate (Table 5.6).

Furthermore, WC undersown resulted in a significantly higher ($P<0.05$) total wheat N uptake compared with Nus and BM undersown, while no significant differences were observed between undersowing treatments on wheat DM production.

Table 5. 6. Effect of cultivation techniques and nitrogen fertilisation on spring wheat biomass and N uptake (May 2014)

	Wheat DM (t ha^{-1}) May	Total Wheat N uptake (kg N ha^{-1}) May
CT	0.504c	21.39c
HINiT	0.429b	15.59b
LINiT	0.242a	9.68a
SED (4 df)	*0.015*	*0.53*
P	***	***
N0	0.382a	13.78a
N70	0.372a	14.69a
N140	0.358a	14.76a
N210	0.455a	18.97b
SED (18 df)	*0.038*	*1.66*
P	*ns*	*
BM	0.3817a	14.78a
Nus	0.3711a	14.80a
WC	0.4230a	17.08b
SED (47 df)	*0.02255*	*0.959*
P	*ns*	*

Values followed by same letter, do not differ significantly at *$P<0.05$; *= $P<0.05$; ***= $P<0.001$; and ns= no significant

Due to significant interactions under WC, N210 resulted in a significantly higher total wheat N uptake compared with any other N rate treatment, at the May assessment (Figure 5.6). Under Nus, N application resulted in a significantly higher total wheat N uptake compared with unfertilised treatment.

Figure 5. 6. Cultivation techniques and undersowing interaction effect on wheat N uptake (May 2014)

Error bars representing average LSD (*P*<0.05)
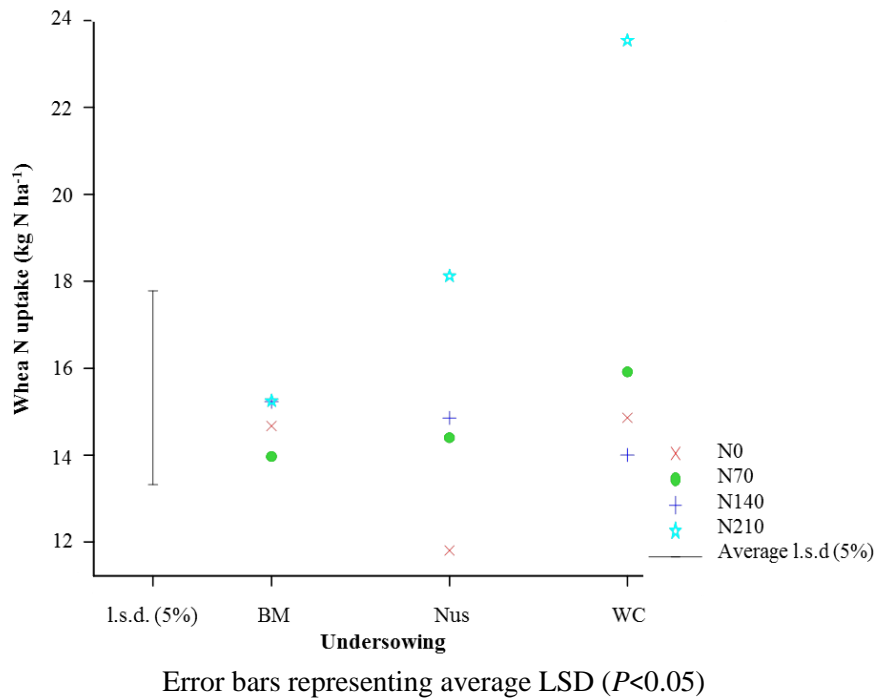
At the July and August assessments, CT resulted in significantly higher wheat DM and total wheat N uptake compared with HINiT and LINiT (Table 5.7).

At the July assessment N140 and N210 significantly increased (*P*<0.01) wheat DM compared with N0 and N70, while at the August assessment N210 resulted in a significantly higher (*P*<0.001) wheat DM, compared specifically with N0. In both assessments times, total wheat N uptake significantly increased (*P*<0.001) with increasing N fertilisation rate.

There were no significant effects of undersowing on wheat biomass and N uptake at the July and August assessments.

Table 5. 7. Effect of cultivation techniques and nitrogen fertilisation on spring wheat biomass and N uptake (July and August 2014)

	Wheat DM (t ha⁻¹) July	Wheat N uptake (kg N ha⁻¹) July	Wheat DM (t ha⁻¹) August	Wheat N uptake (kg N ha⁻¹) August
CT	6.724b	157.0b	11.412b	169.10b
HINiT	4.107a	76.3a	5.809a	80.90a
LINiT	4.287a	81.0a	6.724a	93.50a
SED (4 df)	*0.384*	*7.89*	*0.417*	*8.86*
P	**	***	***	***
N0	4.118a	65.20a	6.786a	86.80a
N70	4.854ab	92.20b	7.480ab	102.7b
N140	5.541b	120.60c	8.434bc	120.3c
N210	5.643b	141.00d	9.227c	148.2d
SED (18 df)	*0.40*	*8.62*	*0.489*	*7.28*
P	**	***	***	***

Values followed by same letter, do not differ significantly at *P<0.05;* *= *P<0.05*, **= *P<0.01*; ***= *P<0.001*; and ns= no significant

Due to significant interactions, at the July assessment, CT resulted in higher wheat N content under Nus and WC than with BM undersown (Figure 5.7).

Figure 5. 7. Cultivation techniques and undersowing interaction effect on wheat N uptake (July 2014)

Error bars representing average LSD (*P<0.05*)
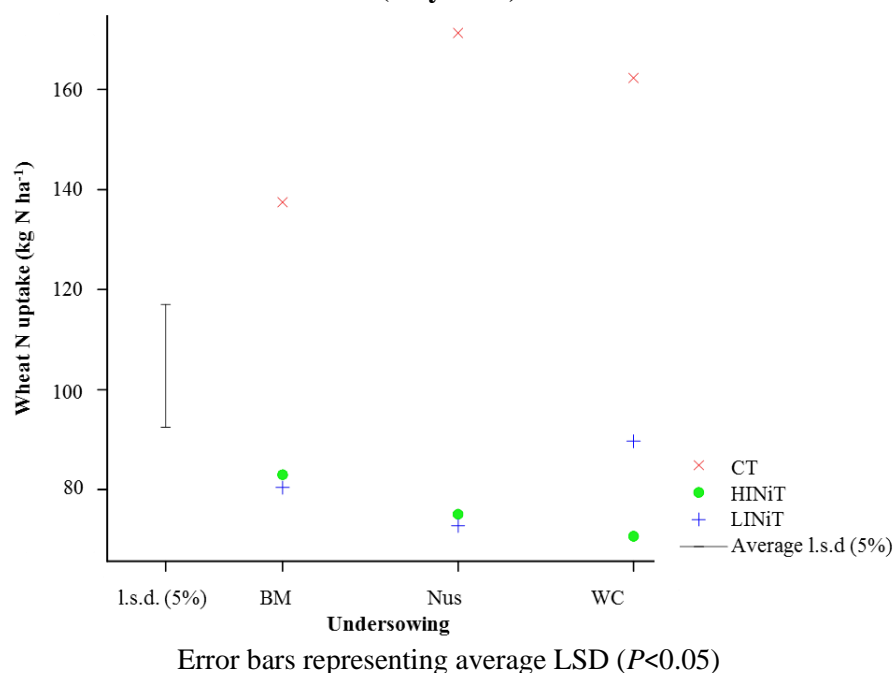
5.3.4. Mid-season weed and legume biomass and nitrogen uptake

May assessment

At this assessment time, weeds were separated by species and grouped into broadleaf and grass weeds. However, total weed DM, broadleaf and grass weeds, were not significantly affected by any treatment structure or interactions (Table 5.8). Nevertheless, HINiT resulted in a significantly higher ($P<0.05$) total weed N uptake compared with CT and LINiT. No significant effect of N fertilisation was observed on total weed N uptake.

Legume DM and N uptake were not significantly affected by cultivation techniques (Table 5.8). N applications, regardless of the N rate, significantly reduced ($P<0.05$) legume DM and N uptake compared with unfertilised treatment (Table 5.8).

Table 5. 8. Effect of cultivation techniques and nitrogen fertilisation on weed and legume biomass and N uptake (May 2014)

	Total weed DM (t ha^{-1}) May	Broadleaf weed DM (t ha^{-1}) May	Grass weed DM (t ha^{-1}) May	Total weed N uptake (kg N ha^{-1}) May	Legume DM (t ha^{-1}) May	Legume N uptake (kg N ha^{-1}) May
CT	0.0107a	0.0107a	0.00001a	0.350a	0.0000001a	0.00001a
HINiT	0.1832a	0.1832a	0.00001a	6.256b	0.00218a	0.0623a
LINiT	0.0573a	0.0530a	0.0043a	1.979a	0.00003a	0.0010a
SED (4 df)	*0.05231*	*0.0522*	*0.00347*	*1.489*	*0.00089*	*0.02534*
P	*ns*	*ns*	*ns*	***	*ns*	*ns*
N0	0.0754a	0.0752a	0.0002a	2.08a	0.002797b	0.07854b
N70	0.0978a	0.0922a	0.0055a	3.43a	0.000111a	0.00437a
N140	0.0804a	0.0804a	0.00001a	2.95a	0.000037a	0.00141a
N210	0.0814a	0.0813a	0.0001a	2.99a	0.0000001a	0.00001a
SED (18 df)	*0.03307*	*0.033*	*0.00387*	*1.006*	*0.00098*	*0.02754*
P	*ns*	*ns*	*ns*	*ns*	***	***

Values followed by same letter, do not differ significantly at *P<0.05;* *= P<0.05, and ns= no significant

Due to significant interactions ($P<0.01$), under N0, HINiT resulted in higher legume DM and N uptake compared with CT and LINiT (Figure 5.8 & 5.9). There were no significant effects of undersowing or any other treatments interactions on legume biomass in May.

Figure 5. 8. Cultivation techniques and nitrogen fertilisation interaction effect on legume biomass (May 2014)

Error bars representing average LSD (*P*<0.05)
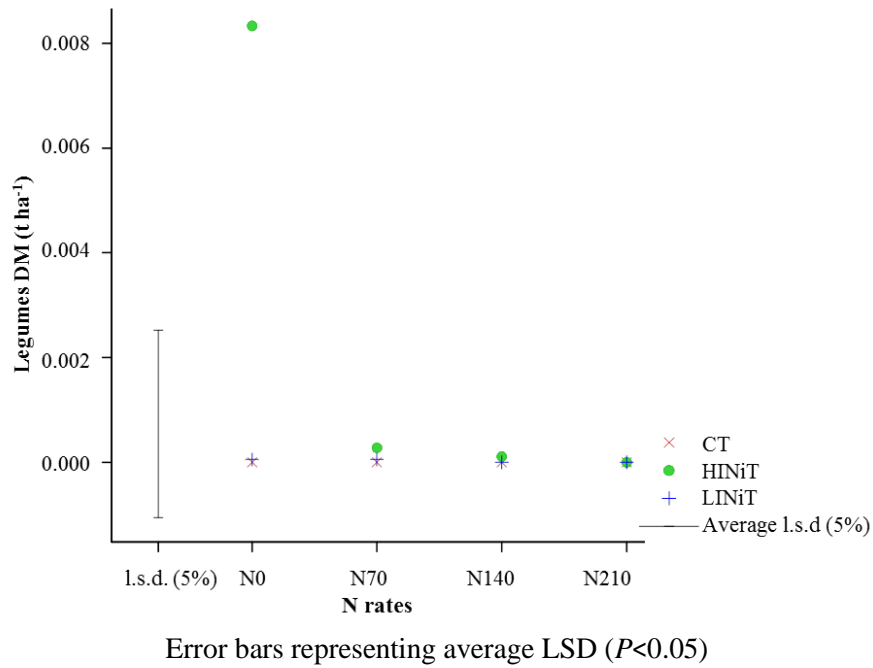
Figure 5. 9. Cultivation techniques and nitrogen fertilisation interaction effect on legume N uptake (May 2014)

Error bars representing average LSD (*P*<0.05)
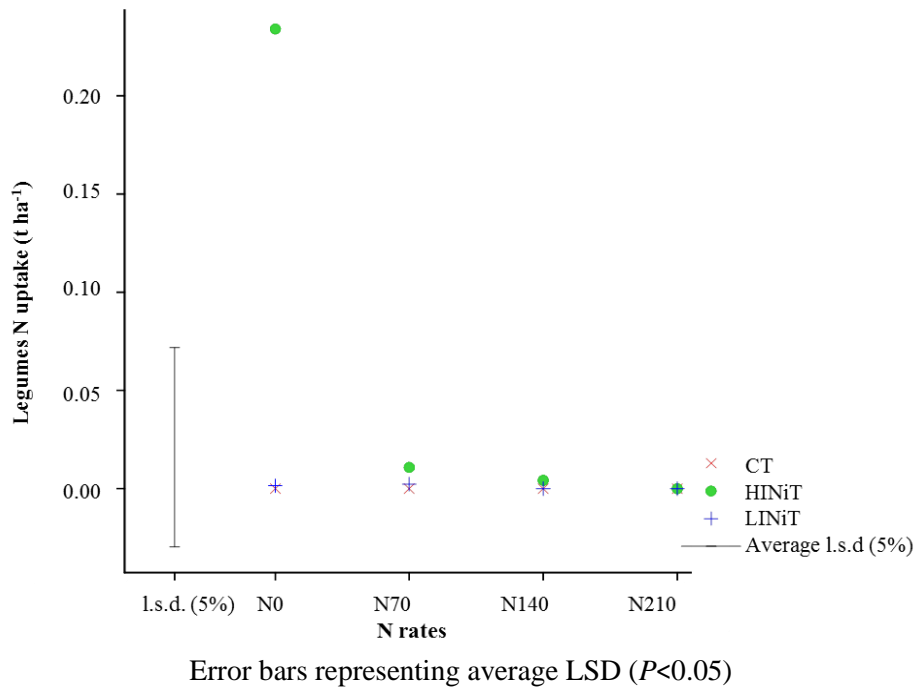
<u>July assessment</u>

CT resulted in a significantly lower ($P<0.01$) total weed DM compared with HINiT and LINiT, while total weed N uptake was significantly higher ($P<0.01$) under HINiT than LINiT, followed by CT (Table 5.9).

At this assessment time, weeds were also separated by species and grouped into broadleaf and grass weeds. Broadleaf weeds DM were significantly higher ($P<0.01$) under HINiT compared with LINiT, followed by CT, while no significant effects of cultivation techniques were observed on grass weeds DM (Table 5.9).

N fertilisation significantly increased ($P<0.001$) total weeds DM and broadleaf weeds DM compared with unfertilised treatment, while no significant effects were observed on grass weeds DM (Table 5.9). Total weed N uptake significantly increased ($P<0.001$) with increasing N rate application, although no significant differences were observed between N70 and N140.

There were no significant effects of cultivation techniques and N fertilisation on legume DM and N uptake.

Table 5. 9. Effect of cultivation techniques and nitrogen fertilisation on weed and legume biomass and N uptake (July 2014)

	Total weed DM (t ha^{-1}) July	Broadleaf weed DM (t ha^{-1}) July	Grass weed DM (t ha^{-1}) July	Total weed N uptake (kg N ha^{-1}) July	Legume DM (t ha^{-1}) July	Legume N uptake (kg N ha^{-1}) July
CT	0.196a	0.122a	0.073a	5.20a	0.0010a	0.005a
HINiT	1.909b	1.512c	0.397a	42.41c	0.0202a	0.277a
LINiT	1.309b	0.815b	0.494a	28.08b	0.0050a	0.102a
SED (4 df)	*0.21740*	*0.2458*	*0.1683*	*4.93*	*0.00705*	*0.1803*
P	**	**	*ns*	**	*ns*	*ns*
N0	0.412a	0.3379a	0.073a	6.25a	0.0134a	0.261a
N70	1.222b	0.9836b	0.239a	22.47b	0.0056a	0.110a
N140	1.332b	0.8981b	0.434a	30.08b	0.0152a	0.119a
N210	1.585b	1.0453b	0.540a	42.10c	0.0008a	0.022a
SED (18 df)	*0.2173*	*0.1565*	*0.2016*	*4.95*	*0.0063*	*0.0996*
P	***	***	*ns*	***	*ns*	*ns*

Values followed by same letter, do not differ significantly at *P<0.05; **= P<0.01;
***=P<0.001*; and ns= no significant

Due to significant interactions, HINiT resulted in significant higher total weed DM under N application rates compared with N0 (Figure 5.10). LINiT resulted in significantly lower total weed DM under N0, compared specifically with N70 and N210 (Figure 5.10).

Figure 5. 10. Cultivation techniques and nitrogen fertilisation interaction effect on weed biomass (July 2014)

Error bars representing average LSD (*P*<0.05)
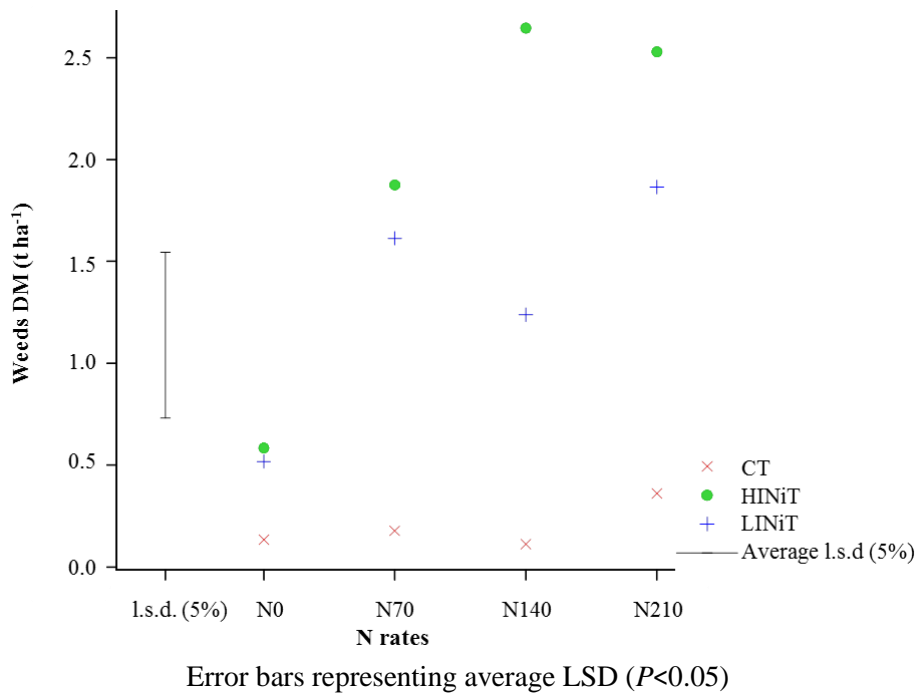
HINiT resulted in significant higher broadleaf weeds DM under N application rates compared with N0, due to significant interactions (Figure 5.11).

Figure 5. 11. Cultivation techniques and nitrogen fertilisation interaction effect on broadleaf weed biomass (July 2014)

Error bars representing average LSD (*P*<0.05)
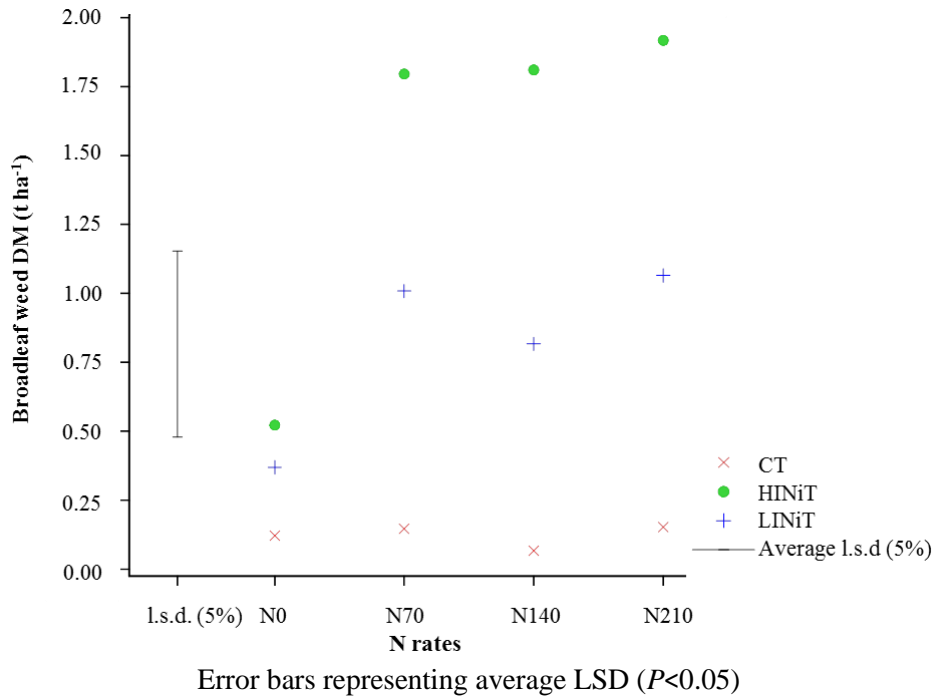
Total weed N uptake was significantly higher under HINiT with N140 and N210, compared specifically with N0 (Figure 5.12). LINiT resulted in a significantly higher total weed N uptake under N210 than specifically with N0.

Figure 5. 12. Cultivation techniques and nitrogen fertilisation interaction effect on weed N uptake (July 2014)

Error bars representing average LSD (*P*<0.05)
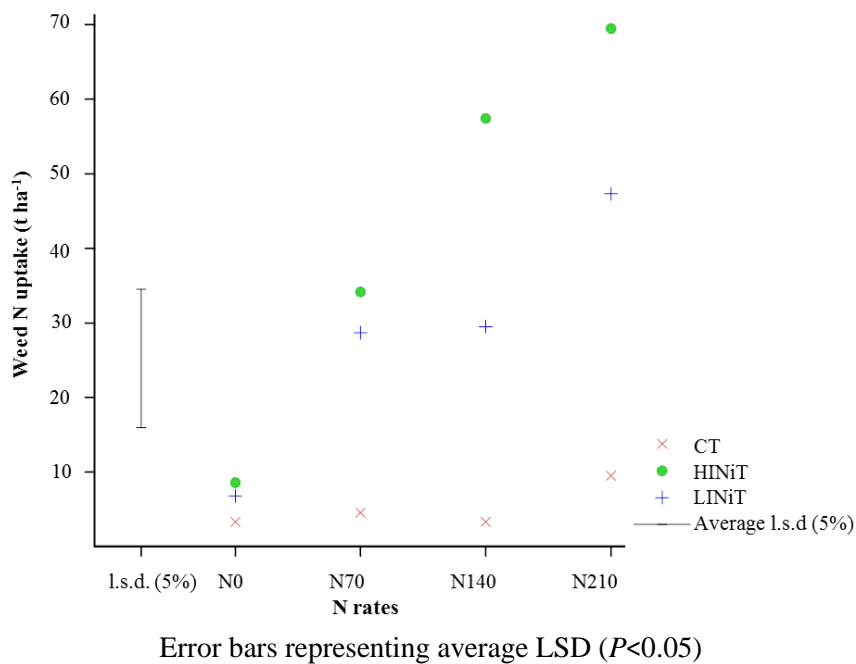
August assessment

CT resulted in significantly lower ($P<0.01$) total weed DM and total weed N uptake than HINiT and LINiT (Table 5.10). Legume DM and N uptake were not significantly affected by cultivation techniques at this assessment time.

Unfertilised treatment resulted in a significantly lower ($P<0.001$) total weed DM compared with N application rates (Table 5.10). Total weed N uptake significantly increased ($P<0.001$) with N rate, although no significant differences were observed between N70 and N140. Legume DM and N uptake were significantly higher ($P<0.01$) under N0 than with any other N rate treatment (Table 5.10).

BM resulted in significantly higher ($P<0.05$) legume DM and N uptake when compared with WC while Nus was statistically similar (Table 5.10). No significant undersowing effect on weed DM and N uptake was observed.

Table 5. 10. Effect of cultivation techniques and nitrogen fertilisation on weeds and legumes biomass and N uptake (August 2014)

	Total weed DM (t ha^{-1}) August	Total weed N uptake (kg N ha^{-1}) August	Legume DM (t ha^{-1}) August	Legume N uptake (kg N ha^{-1}) August
CT	0.177a	3.90a	0.0063a	0.16a
HINiT	2.292b	34.98b	0.0483a	1.38a
LINiT	2.220b	34.18b	0.0184a	0.48a
SED (4 df)	*0.2569*	*4.00*	*0.0155*	*0.432*
P	**	**	*ns*	*ns*
N0	0.851a	12.12a	0.0733b	2.1258b
N70	1.970b	24.13b	0.0155a	0.3746a
N140	1.718b	27.19b	0.0080a	0.1949a
N210	1.713b	33.98c	0.0006a	0.0029a
SED (18 df)	*0.2075*	*2.65*	*0.0185*	*0.545*
P	***	***	**	**
BM	1.528a	23.50a	0.0409b	1.1909b
Nus	1.479a	23.80a	0.0226ab	0.5957ab
WC	1.683a	25.80a	0.0096a	0.2370a
SED (48 df)	*0.2233*	*2.90*	*0.0116*	*0.336*
P	*ns*	*ns*	*	*

Values followed by same letter, do not differ significantly at *P<0.05;* *= *P<0.05*, **= *P<0.01*; ***= *P<0.001*; and ns= no significant

Furthermore, at the August assessment, due to significant interactions, HINiT and LINiT resulted in lower weed DM with N0, while CT did not show significant differences with any N treatments (Figure 5.13).

Figure 5. 13. Cultivation techniques and nitrogen fertilisation interaction effect on weed biomass (August 2014)

Error bars representing average LSD ($P<0.05$)
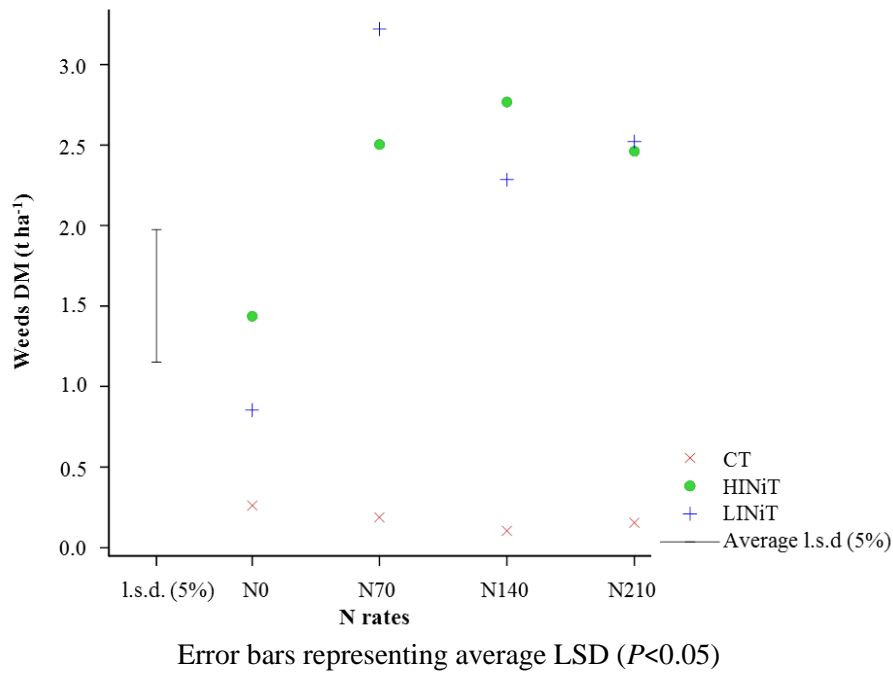
In addition, HINiT resulted in a lower total weed N uptake at N0, compared specifically with N140 and N210 (Figure 5.14). LINiT resulted in significantly lower total weed N uptake under N0 compared with any other N rate application, while CT did not show significant differences with any N rate treatments on weed N uptake (Figure 5.14).

Due to significant treatments interaction, HINiT resulted in higher legume biomass and N uptake than CT and LINiT with N0 (Figure 5.15 & 5.16).
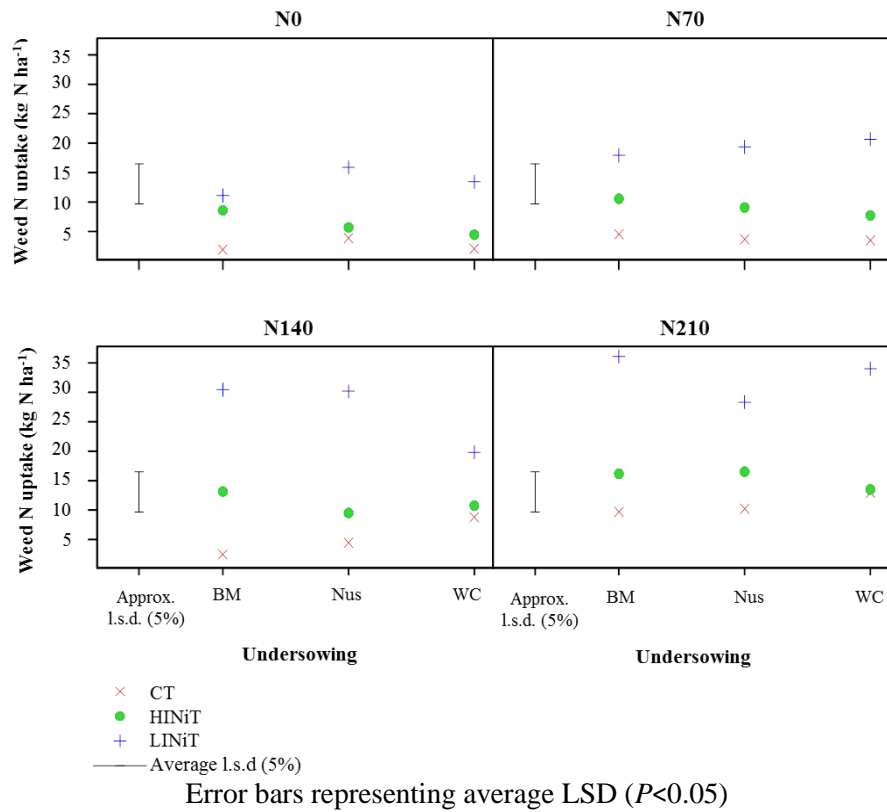
Figure 5. 14. Cultivation techniques and nitrogen fertilisation interaction effect on weed N uptake (August 2014)
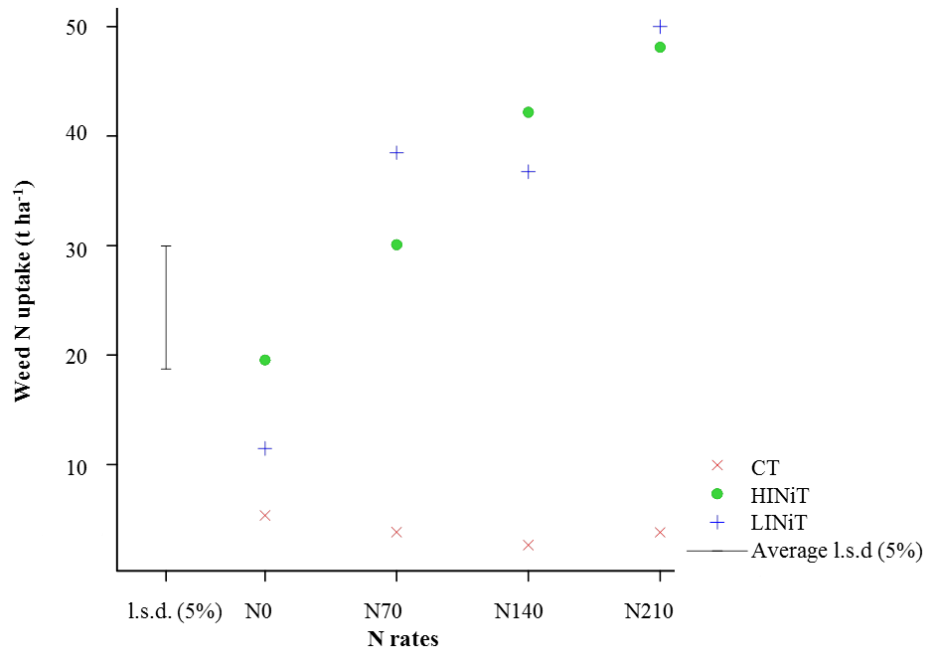
Error bars representing average LSD (*P*<0.05)

Figure 5. 15. Cultivation techniques and nitrogen fertilisation interaction effect on legume biomass (August 2014)
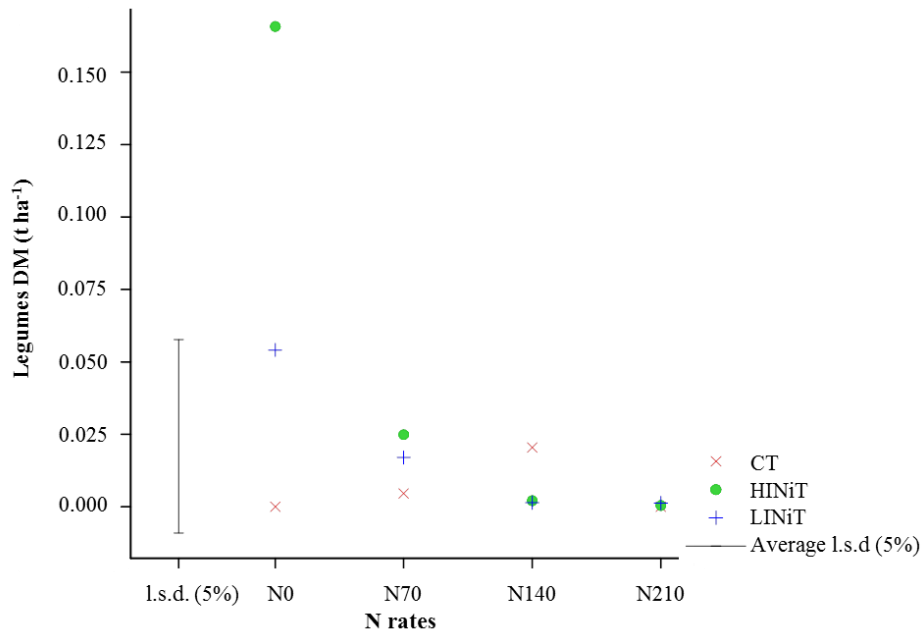
Error bars representing average LSD (*P*<0.05)

Figure 5. 16. Cultivation techniques and nitrogen fertilisation interaction effect on legume N uptake (August 2014)

Error bars representing average LSD (*P*<0.05)
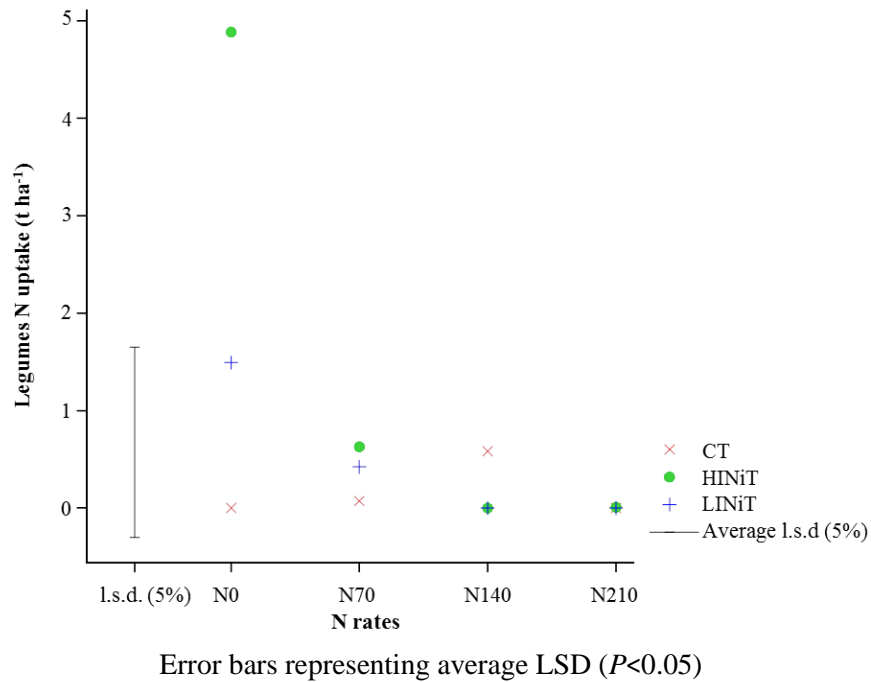
5.3.5. Weed species composition

In the July assessment, weeds were separated by species, recording a total of 29 weed species, five were grass weed species and 24 broadleaf weed species. The list of all weed species recorded can be found in Appendix 2. The dominant weed species were *Sinapsis arvensis* L., *Avena sativa* L., *Stellaria media* L., and *Galium aparine* L., accounting 35.1%, 26.9%, 15.2% and 14.8% of the total weed biomass recorded.

Within the dominant weed species, *Sinapsis arvensis* and *Stellaria media,* were the only species significantly affected by management treatments (Table 5.11). Other species occurred too infrequently to permit treatments effects to be appropriatly tested or were not significantly affected by any treatment.

Table 5. 11. Effect of cultivation techniques, nitrogen fertilisation and undersowing on *Sinapsis arvensis* **L. and** *Stellaria media* **L. biomass (July 2014)**

	Stellaria media L. DM (t ha^{-1})	*Sinapsis arvensis* L. DM (t ha^{-1})
CT	0.0081a	0.0607a
HINiT	0.3359b	0.9070b
LINiT	0.1557a	0.1874a
SED (4 df)	*0.0579*	*0.1104*
P	**	**
N0	0.0693a	0.1097a
N70	0.2701b	0.3671b
N140	0.1669ab	0.4331bc
N210	0.1601ab	0.6304c
SED (18 df)	*0.0574*	*0.1103*
P	*	***
BM	0.1575ab	0.269a
Nus	0.104a	0.408a
WC	0.2383b	0.477a
SED (48 df)	*0.0523*	*0.0948*
P	*	*ns*

Values followed by same letter, do not differ significantly at *P<0.05;* *= *P*<0.05, **= *P*<0.01; ***= *P*<0.001; and ns= no significant

Stellaria media and *Sinapsis arvensis* DM were significantly higher (*P*<0.01) under HINiT compared with CT and LINiT (Table 5.11). *Stellaria media* DM was significantly higher (*P*<0.05) with 70 kg N ha^{-1}, specifically compared with N0, while WC significantly increased its DM (*P*<0.05), compared particularly with Nus. *Sinapsis arvensis* DM was significantly higher (*P*<0.001) with N210 compared with N70 and N0 (*P*<0.001).

Due to significant interactions, HINiT increased *Sinapsis arvensis* DM when N was applied compared with unfertilised treatment, while no significant differences were observed between N rates under CT and LINiT (Figure 5.17).

Figure 5. 17. Cultivation techniques and nitrogen fertilisation interaction effect on *Sinapsis arvensis* L. biomass (July 2014)

Error bars representing average LSD (*P*<0.05)
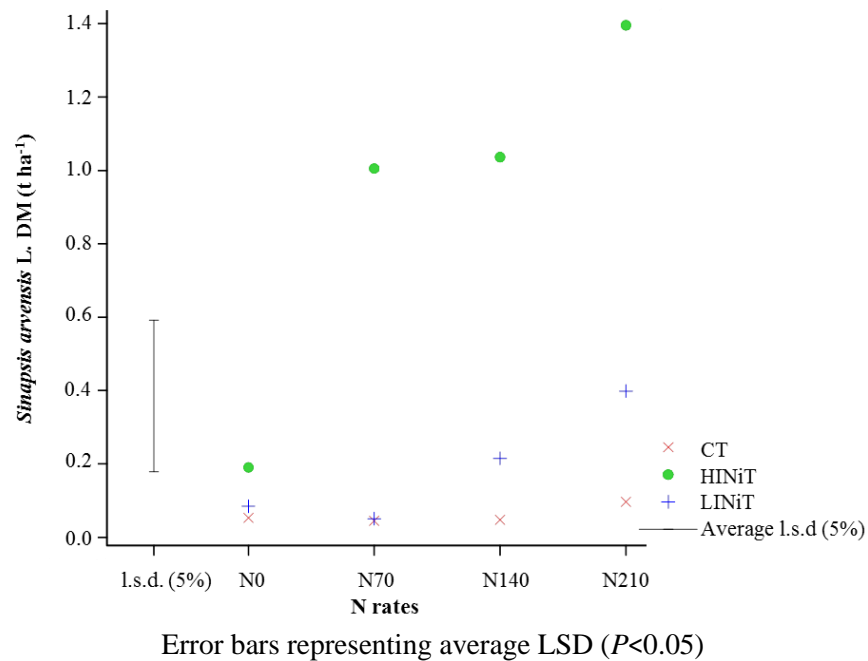
In addition, HINiT resulted in significant higher *Sinapsis arvensis* DM with N70 and N210 under undersown WC or Nus, while no significant differences were observed with BM (Figure 5.18). HINiT increased *Sinapsis arvensis* DM compared with CT and LINiT under BM undersown and N140. Under WC and N140, HINiT increased *Sinapsis arvensis* DM compared with CT.

Figure 5. 18. Cultivation techniques, nitrogen fertilisation and undersowing interaction effect on *Sinapsis arvensis* L. biomass (July 2014)
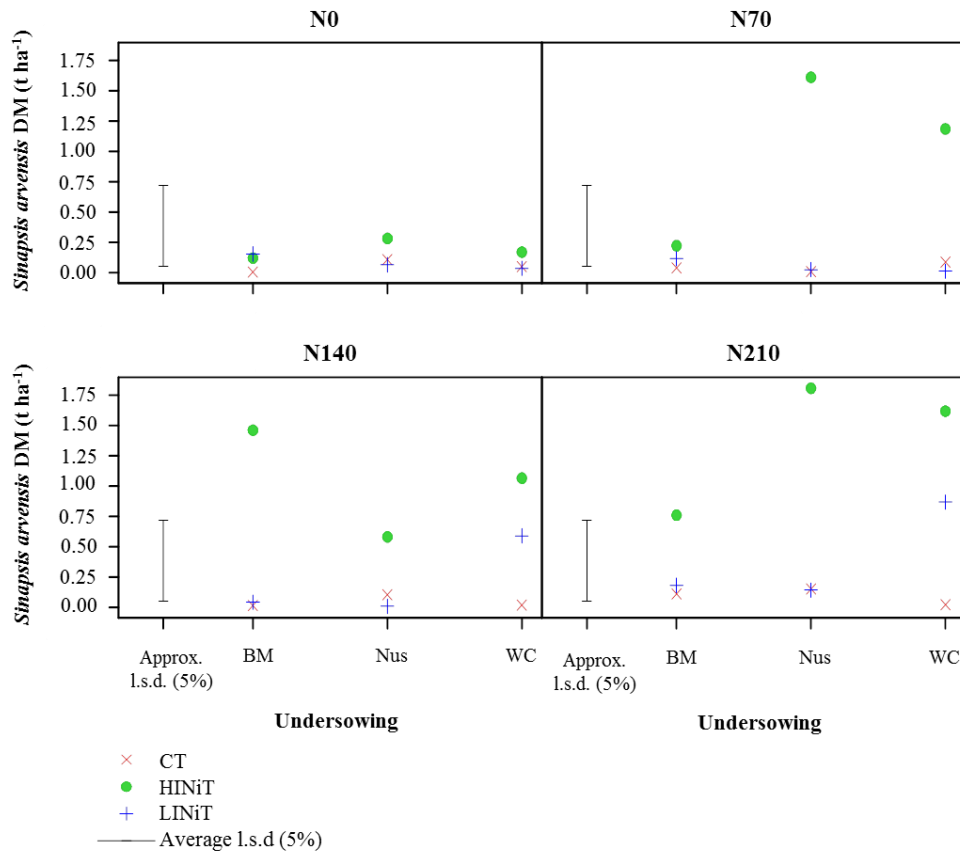
Error bars representing average LSD (*P*<0.05)

5.3.6. Plant height and ears number

Wheat crop height was not significantly affected by cultivation techniques treatments (Table 5.12). However, N fertilisation treatments gave significantly (*P*<0.001) taller plants with increasing N rates, although no significant differences were observed between N140 and N210 (Table 5.12). There were no significant effects of undersowing treatment or any other treatment interaction on plant height.

Wheat ear number per unit area was significantly affected by cultivation treatments (*P*<0.05) resulting in higher number under CT, compared specifically with LINiT (Table 5.12). No significant effects were observed on ears number by N fertilisation or undersowing treatments.

Table 5. 12. Cultivation techniques and nitrogen fertilisation effect on spring wheat height and ears number

	Plant height (cm)	Ears (number m^{-2})
CT	88.26a	463.80b
HINiT	83.88a	367.90ab
LINiT	84.26a	318.60a
SED (*4 df*)	*1.316*	*35.94*
P	*ns*	*
N0	75.41a	370.00a
N70	84.65b	391.90a
N140	90.00c	376.90a
N210	91.81c	395.00a
SED (18 *df*)	*1.324*	*26.96*
P	***	*ns*

Values followed by same letter, do not differ significantly at *P<0.05; *= P<0.05; ***=P<0.001;* and ns= no significant

Due to significant interactions, CT produced taller plants than HINiT and LINiT under unfertilised conditions (Figure 5.19). No significant differences were observed between tillage treatments when N was applied.

Figure 5. 19. Cultivation techniques and nitrogen fertilisation interaction effect on spring wheat height
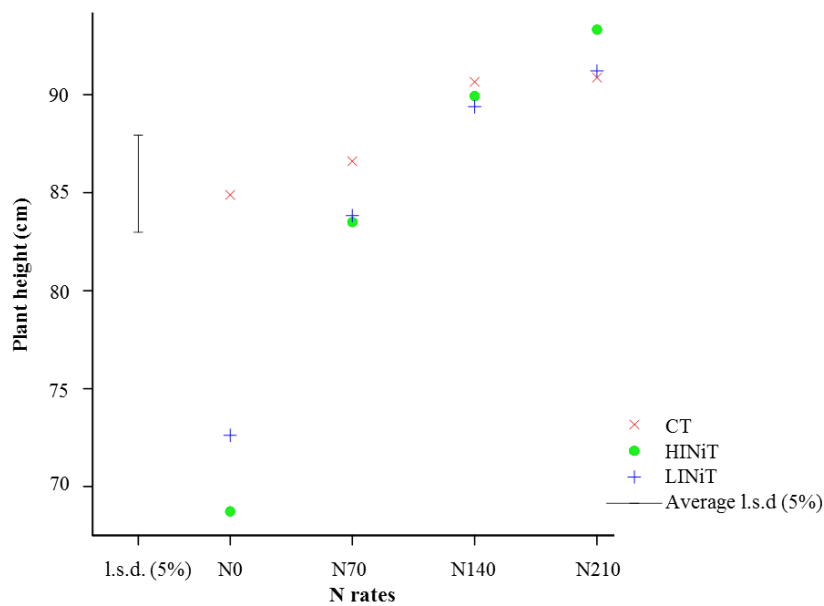
Error bars representing average LSD (*P*<0.05)

CT resulted in higher number of ears compared with HINiT and LINiT under BM undersown and Nus, due to significant interactions (Figure 5.20). Under undersown WC, a higher number of ears were recorded under CT, compared specifically with LINiT.

Figure 5. 20. Cultivation techniques and nitrogen fertilisation interaction effect on spring wheat ears number

Error bars representing average LSD (*P*<0.05)
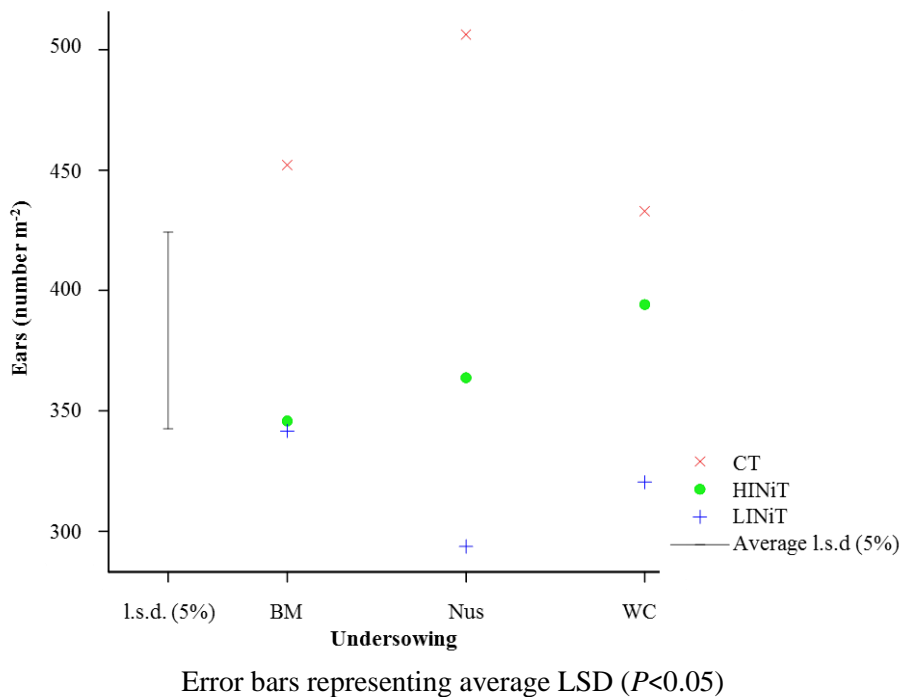
5.3.7. Diseases scoring

The severity of two diseases was evaluated during the 2014 cropping season, *Zymoseptoria tritici* Desm. Quaedvlieg & Crous (leaf blotch of wheat) and *Puccina triticina* Erikss. (leaf rust of wheat). Regardless of the management treatments, the mean severity of *Zymoseptoria tritici* and *Puccina triticina* were 26.1% and 2.1% respectively. However, there were not statistically significant effects of any management treatment or treatments interactions on the severity of these diseases, even when data variability was reduced by transforming raw data.

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5.3.8. Final biological harvest

<u>Ear, straw and total wheat biomass</u>

Ear, straw and total wheat biomass were significantly affected ($P<0.01$) by cultivation techniques, with CT resulting in higher biomass compared with LINiT and HINiT (Table 5.13). N140 and N210 significantly increased ear ($P<0.01$), straw ($P<0.001$) and total wheat DM ($P<0.01$), compared with N70 and N0 (Table 5.13). No significant effects were observed by undersowing treatments on ear, straw and total wheat DM.

Table 5. 13. Cultivation techniques and nitrogen fertilisation effect on ears, straw and total wheat biomass

	Ears DM (t ha^{-1})	Straw DM (t ha^{-1})	Total wheat DM (t ha^{-1})
CT	6.888b	5.015b	11.821b
HINiT	3.359a	2.913a	6.272a
LINiT	3.991a	3.176a	7.167a
SED (4 df)	*0.3986*	*0.2808*	*0.611*
P	**	**	**
N0	4.101a	3.101a	7.203a
N70	4.184a	3.407a	7.591a
N140	5.316b	4.046b	9.254b
N210	5.382b	4.251b	9.633b
SED (18 df)	*0.3849*	*0.2461*	*0.593*
P	**	***	**

Values followed by same letter, do not differ significantly at *P<0.05; **= P<0.01*; and
***=P<0.001

Due to significant interactions, with BM undersown, CT resulted in a significant higher straw DM than LINiT, followed by HINiT. However, with WC and Nus, CT resulted in higher straw DM compared with non-inversion tillage treatments (Figure 5.21).

Figure 5. 21. Cultivation techniques and undersowing interaction effect on spring wheat straw biomass

Error bars representing average LSD (*P*<0.05)
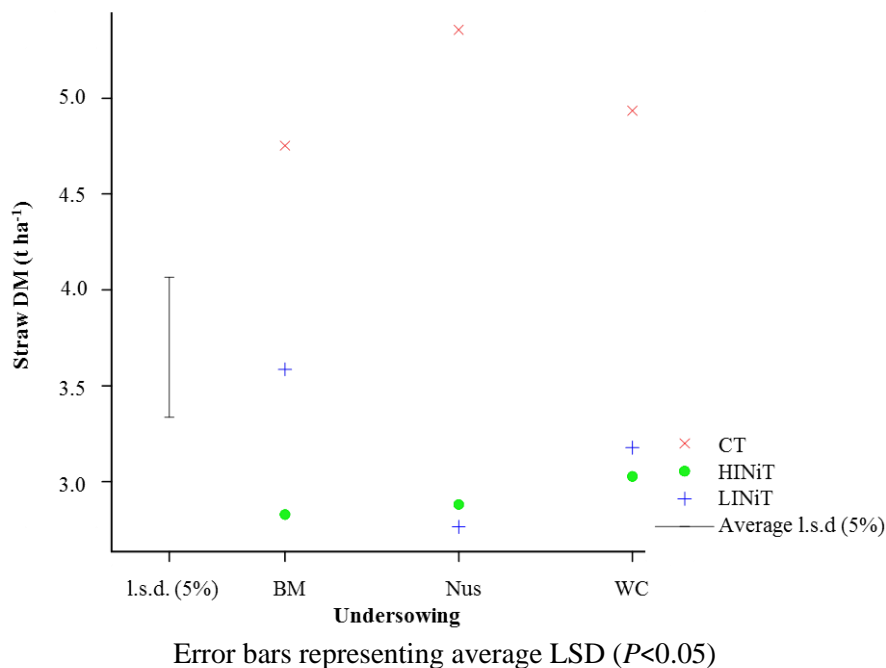
TGW, grains per ear and grain yield

Thousand grain weight (TGW) was not significantly affected by cultivation techniques (Table 5.14). Increasing N rate significantly increased (*P*<0.01) TGW, although no significant differences were observed between N70 and N140.

Numbers of grains per ear was significantly (*P*<0.001) increased under CT than LINiT, followed by HINiT (Table 5.14). Additionally, N140 and N210 applications significantly increased (*P*<0.001) grains number per ear compared with N0 and N70. Due to significant interactions, LINiT and HINiT significantly increased grain number per ear under N140 and N210 compared with N0 and N70, while CT did not differ between N rate applications (Figure 5.22).

Overall the final spring wheat grain yield mean obtained in the 2014 cropping season was 3.69 t ha^{-1}, which was lower than the 2013 final yield (5.65 t ha^{-1}). Among tillage treatments, CT resulted in a significantly higher (*P*<0.01) grain yield compared with HINiT and LINiT (Table 5.14). N fertilisation significantly affected (*P*<0.01) the final grain yield, with higher yield with 140 and 210 kg N ha^{-1} compared with N70 and N0 (Table 5.14).

Table 5. 14. Cultivation techniques and nitrogen fertilisation effect on spring wheat TGW, grains per ear, final grain yield and harvest index

	TGW (g)	Grain per ears	Grain yield (t ha⁻¹)	HI (%)
CT	32.37a	36.27c	5.37b	45.04b
HINiT	32.65a	21.44a	2.53a	39.96a
LINiT	33.69a	29.69b	3.20a	44.24b
SED (4 df)	*0.764*	*0.941*	*0.266*	*0.695*
P	*ns*	*****	****	****
N0	34.60c	23.70a	3.10a	41.76a
N70	32.99b	25.53a	3.26a	42.90a
N140	32.83b	33.34b	4.18b	44.05a
N210	31.19a	33.96b	4.25b	43.61a
SED (18 df)	*0.737*	*1.24*	*0.290*	*1.166*
P	****	*****	****	*ns*

Values followed by same letter, do not differ significantly at *P<0.05; **= P<0.01; ***=P<0.001;* and ns= no significant

Figure 5. 22. Cultivation techniques and nitrogen fertilisation interaction effect on spring wheat grains per ear
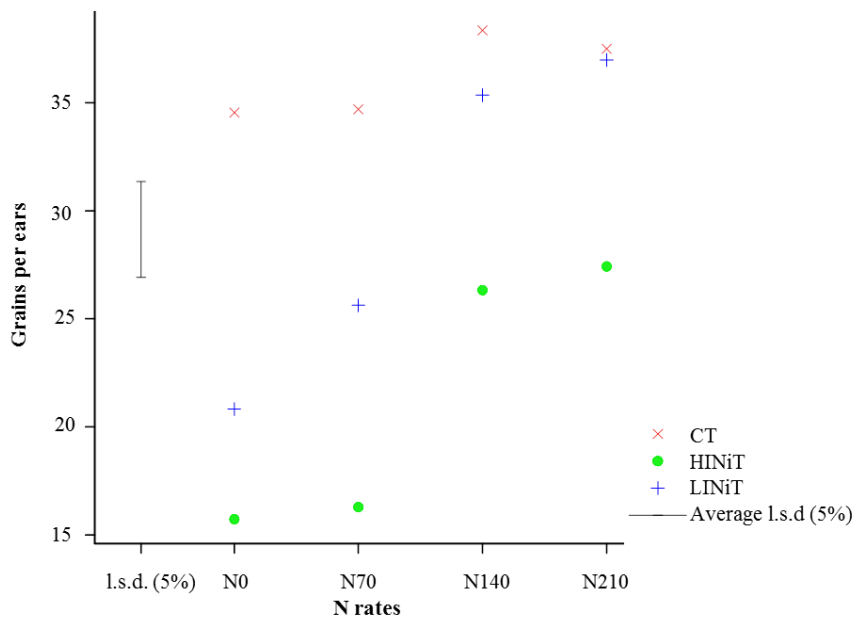
Error bars representing average LSD (*P<0.05*)

Harvest index (HI) was significantly higher (*P<0.01*) under CT and LINiT compared with HINiT (Table 5.14). However, N fertilisation did not significantly affect HI. Due to significant interactions, higher HI was observed under CT than HINiT and LINiT when BM was undersown. Under Nus, LINiT resulted in higher HI than CT, while with

WC, non-inversion tillage treatments had higher HI than CT (Figure 5.23). No significant effects of undersowing treatments were observed on TGW, grains per ear, final grain yield or HI.

Figure 5. 23. Cultivation techniques and undersowing interaction effect on spring wheat harvest index

Error bars representing average LSD (*P*<0.05)
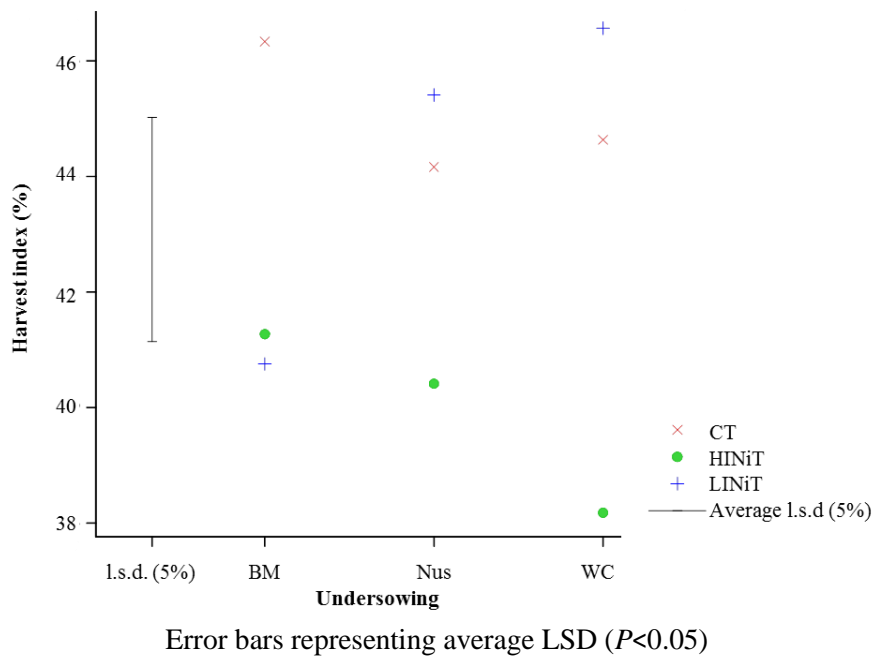
Wheat nitrogen yield

CT resulted in significantly higher (*P*<0.001) total wheat and grain N uptake compared with HINiT and LINiT (Table 5.15). Grain protein and N harvest index (NHI) were not significantly affected by cultivation techniques treatments.

Total wheat N uptake significantly increased (*P*<0.001) with increasing N rate, although no significant differences were observed between N0 and N70 (Table 5.15). Total grain N uptake was significantly higher (*P*<0.001) with N140 and N210 compared with N0 and N70. Grain protein significantly increased (*P*<0.001) with N rate although no significant differences were observed between N0 and N70. NHI was not significantly affected by N fertilisation.

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Table 5. 15. Cultivation techniques and nitrogen fertilisation effect on total wheat and grain N uptake, grain protein content, and N harvest index

	Total wheat N uptake (kg N ha^{-1})	Total grain N uptake (kg N ha^{-1})	Grain protein (%)	NHI (%)
CT	155.60b	120.60b	12.757a	77.05a
HINiT	71.90a	52.54a	11.986a	72.77a
LINiT	89.10a	67.25a	11.968a	74.51a
SED (4 df)	*8.87*	*6.57*	*0.3173*	*1.858*
P	*****	*****	*ns*	*ns*
N0	79.70a	61.38a	11.17a	75.41a
N70	88.20a	66.02a	11.51a	73.85a
N140	117.70b	91.96b	12.60b	76.81a
N210	136.70c	101.15b	13.66c	73.05a
SED (18 df)	*7.00*	*5.93*	*0.3819*	*1.769*
P	*****	*****	*****	*ns*

Values followed by same letter, do not differ significantly at *P<0.05; ***= P<0.001*; and ns=no significant

Wheat nitrogen efficiency

N-use efficiency (NUE) was significantly higher (*P*<0.05) under CT and LINiT than HINiT (Table 18). N uptake efficiency (NUpE) was significantly higher (*P*<0.001) under CT than LINiT, followed by HINiT (Table 5.16), while no significant effects of cultivation techniques were observed on N utilisation efficiency (NUtE).

NUE and NUpE significantly decreased (*P*<0.001) when increasing N fertilisation rate, although no significantly differences were observed between N70 and N140 (Table 5.16). NUtE was significantly lower (*P*<0.001) under N210 compared with any other N rate.

Table 5. 16. Cultivation techniques and nitrogen fertilisation effect on N- efficiency parameters

	NUE (kg kg^{-1})	NUpE (kg kg^{-1})	NUtE (kg kg^{-1})
CT	22.85b	0.6358c	34.83a
HINiT	18.82a	0.5202a	35.39a
LINiT	21.54b	0.5739b	36.23a
SED (4 df)	*0.68*	*0.01257*	*1.053*
P	*	**	*ns*
N0	34.38c	0.8890c	38.69b
N70	19.83b	0.5301b	37.06b
N140	17.47b	0.4836b	35.24b
N210	12.60a	0.4037a	30.94a
SED (18 df)	*1.4*	*0.03188*	*1.677*
P	***	***	***

Values followed by same letter, do not differ significantly at *P<0.05;* *= *P<*0.05; **= *P<*0.01; ***= *P<*0.001; and ns= no significant

Weeds and legumes biomass and nitrogen yield

At harvest time, CT resulted in a significantly lower (*P<*0.05) weed DM and total weed N uptake compared with the non-inversion tillage treatments (Table 5.17). Additionally, N fertilisation significantly increased (*P<*0.01) weed DM compared with unfertilised treatment. Total weed N uptake was significantly higher (*P<*0.001) under N210, compared specifically with N0. No significant effects of undersowing treatments were observed on total weed DM and N uptake.

Legume biomass production at harvest time was not significantly affected by cultivation techniques and N fertilisation treatments (Table 5.17). However, legume N uptake was significantly lower (*P<*0.05) with N fertilisation, compared with unfertilised treatment. BM resulted in significantly higher (*P<*0.01) legume DM and N uptake than WC and Nus (Table 5.17).

There were no significant treatments interaction effects on weed and legume DM and N uptake.

Table 5. 17. Cultivation techniques, nitrogen fertilisation and undersowing effects on weed and legume biomass and N uptake (Harvest 2014)

	Weed DM (t ha⁻¹)	Weed N uptake (kg N ha⁻¹)	Legume DM (t ha⁻¹)	Legume N uptake (kg N ha⁻¹)
CT	0.1403a	3.61a	0.049a	1.24a
HINiT	1.3848b	22.05b	0.119a	4.12a
LINiT	1.1888b	21.38b	0.112a	3.53a
SED (4 df)	*0.2666*	*4.12*	*0.0519*	*2.09*
P	*	**	*ns*	*ns*
N0	0.4972a	8.32a	0.241	8.125b
N70	1.0939b	15.81b	0.049	1.454a
N140	0.8732b	14.30ab	0.074	1.944a
N210	1.1542b	24.29c	0.009	0.335a
SED (18 df)	*0.1639*	*2.987*	*0.0846*	*2.872*
P	**	***	*ns*	*
BM	0.887a	15.47a	0.20528b	6.756b
Nus	0.920a	15.90a	0.04087a	1.149a
WC	0.907a	15.67a	0.03353a	0.988a
SED (47 df)	*0.1284*	*2.197*	*0.0515*	*1.854*
P	*ns*	*ns*	**	**

Values followed by same letter, do not differ significantly at *P<0.05;* *= *P*<0.05; **= *P*<0.01; ***= *P*<0.001; and ns= no significant

5.3.9. Soil mineral nitrogen

Throughout the 2014 cropping season, cultivation technique effects on soil mineral N (SMN) were only statistically evident at the June, July and August assessments (Figure 5.24). In June, CT resulted in significant higher (*P*<0.001) SMN content than LINiT, followed by HINiT, while in July and August, SMN content was significantly higher under CT than LINiT and HINiT.

N fertilisation significantly affected SMN from June till August, although differences between treatments diminished with time (Figure 5.25). In June, increasing N rate significantly increased (*P*<0.001) SMN content, while in July, N0 and N70 resulted in significantly lower (*P*<0.001) SMN, compared with N140 and N210. At the August assessment, higher (*P*<0.01) SMN was observed with 210 kg N ha⁻¹ application compared with any other N rate.

No significant undersowing effect on SMN was observed at any assessment time.

Figure 5. 24. Soil mineral nitrogen (kg N ha⁻¹) under three cultivation techniques

Error bars representing LSD (*P*<0.05) at each month of assessment

Figure 5. 25. Soil mineral nitrogen (kg N ha⁻¹) under four nitrogen fertilisation treatments

Error bars representing LSD (*P*<0.05) at each month of assessment
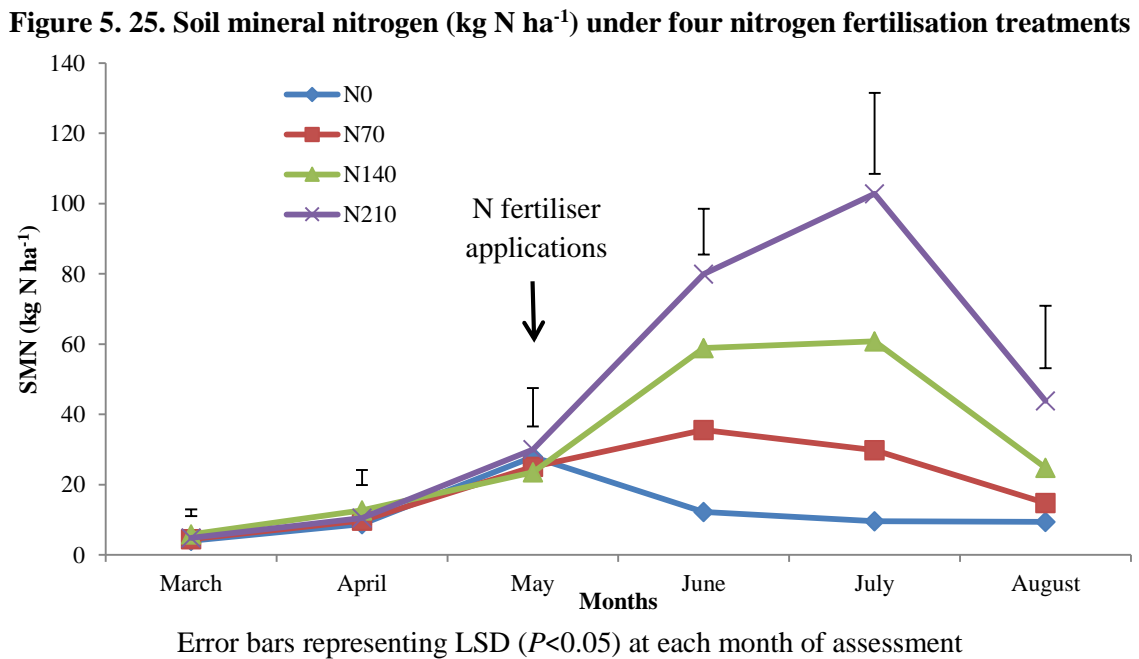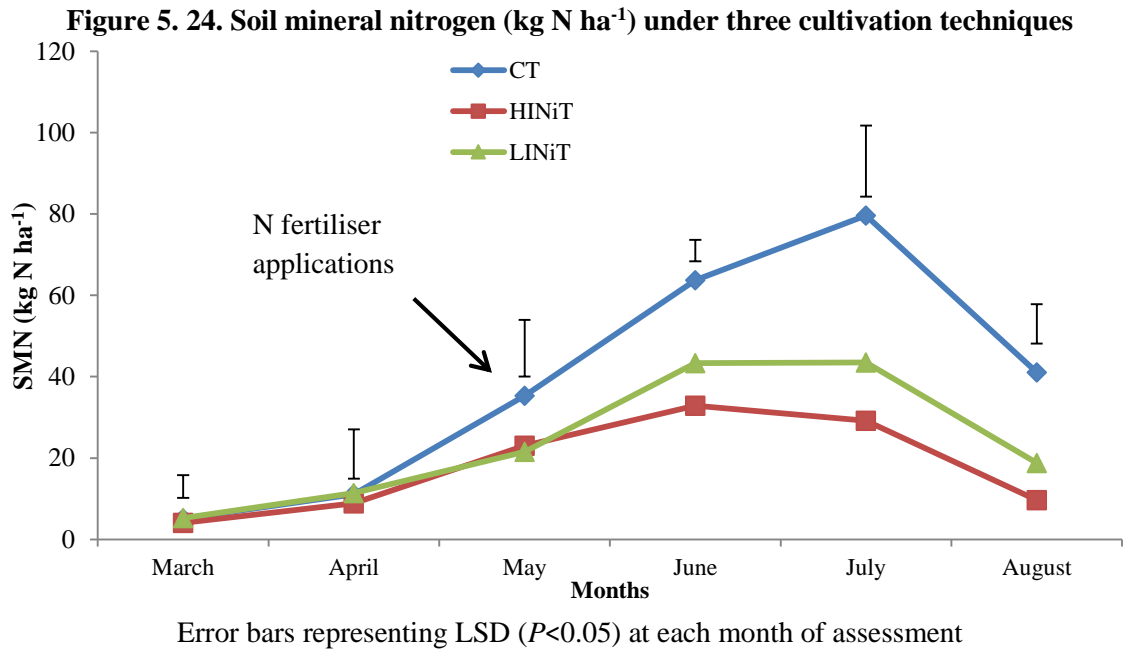
Due to significant interactions, at the July assessment, under N210, CT resulted in higher SMN content than LINiT and HINiT, while with N140, CT resulted in similar SMN content than LINiT but higher than HINiT (Figure 5.26).

Figure 5. 26. Cultivation techniques and nitrogen fertilisation interaction effect on soil mineral nitrogen content (July 2014)

Error bars representing average LSD (*P*<0.05)
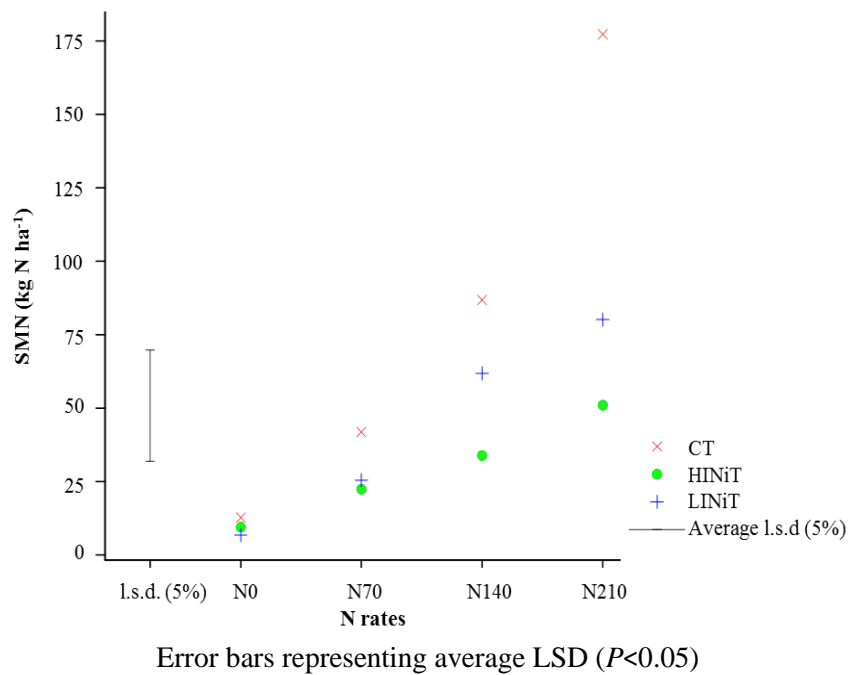
In August, under BM, CT resulted in similar SMN content than LINiT but higher than HINiT (Figure 5.27). Under Nus, higher SMN was observed with CT than LINiT, followed by HINiT. Under WC, CT resulted in higher SMN content than LINiT and HINiT.

Figure 5. 27. Cultivation techniques and undersowing interaction effect soil mineral nitrogen content (August 2014)

Error bars representing average LSD (*P*<0.05)
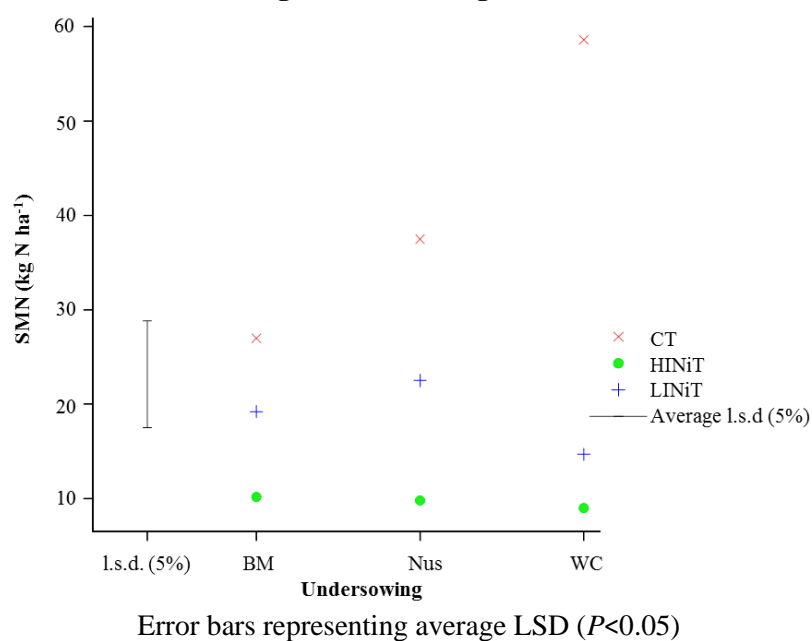
In addition also in August, with N140 and N210, CT resulted in higher SMN under Nus compared specifically with HINiT, while under WC under CT resulted in higher SMN than with HINiT and LINiT (Figure 5.28).

Figure 5. 28. Effect of cultivation techniques, nitrogen fertilisation and undersowing interaction on soil mineral nitrogen (kg N ha⁻¹) (August 2014)
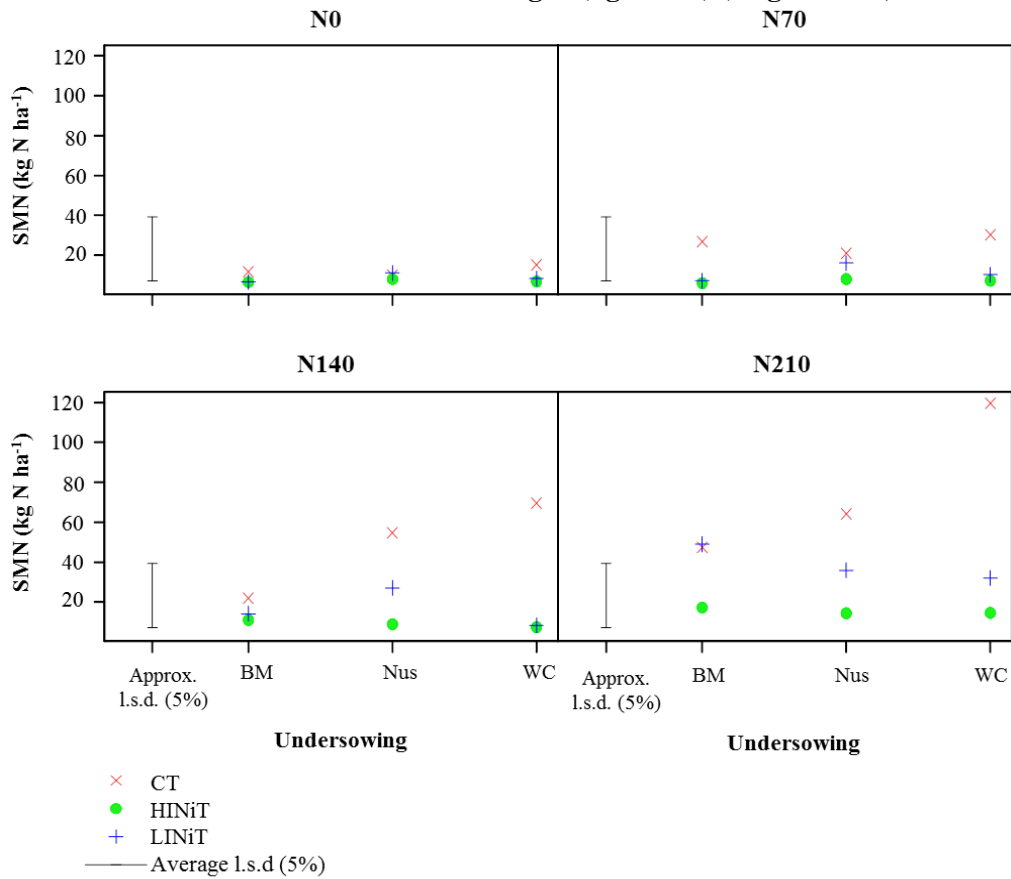
Error bars representing average LSD (*P*<0.05)

Figure 5.29 and 5.30 represent SMN content and total wheat N uptake under cultivation techniques and N fertilisation rates treatments at each month of assessment. Wheat N uptake, in May, was high under CT while SMN content was statistically similar between cultivation techniques treatments (Figure 5.29). In July and August, wheat N uptake and SMN content were significantly higher under CT compared with HINiT and LINiT.

Figure 5. 29. Soil mineral nitrogen (kg N ha^{-1}) and total wheat N uptake under three cultivation techniques at each month of assessment
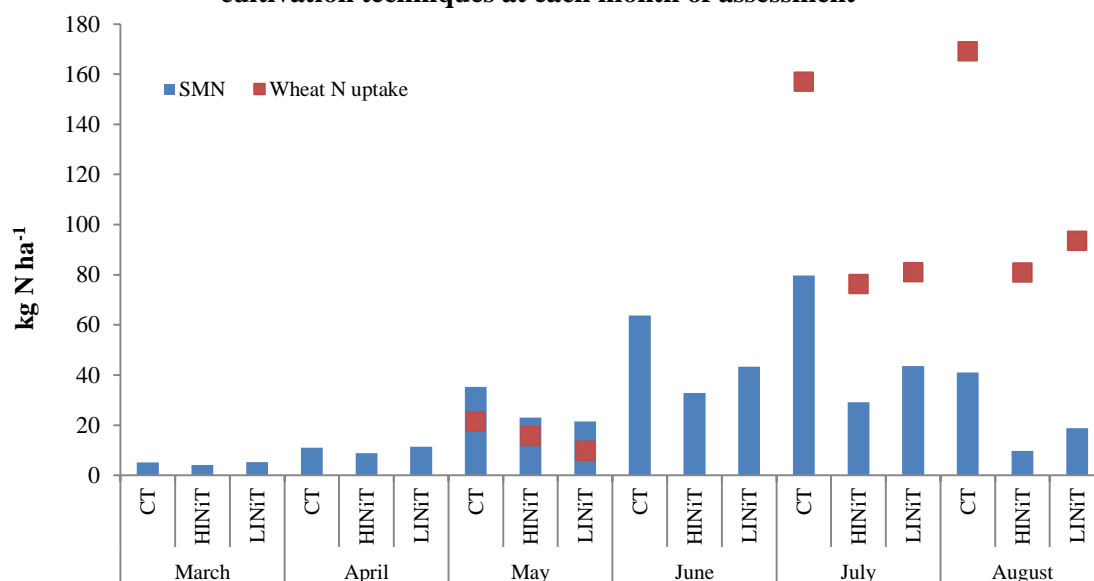
	March	April	May	June	July	August
SMN (LSD)	5.597^{ns}	12.107^{ns}	13.92^{ns}	5.3***	17.51*	9.67**
Wheat N uptake (LSD)	-	-	1.471***	-	21.91***	24.59***

LSD at *P*<0.05 at each month of assessment; *= *P*<0.05; **= *P*<0.01; ***= *P*<0.001; and ns= no significant

N fertilisation in May increased wheat N uptake while SMN levels were not significantly affected (Figure 5.30). In July and August, wheat N uptake increased as SMN level increased by the N rates.

Figure 5. 30. Soil mineral nitrogen (kg N ha^{-1}) and total wheat N uptake under four N fertilisation rates at each month of assessment

	May	June	July	August
SMN (LSD)	10.95^{ns}	13.01***	23.09***	17.73**
Wheat N uptake (LSD)	3.489*	-	18.11***	15.29***
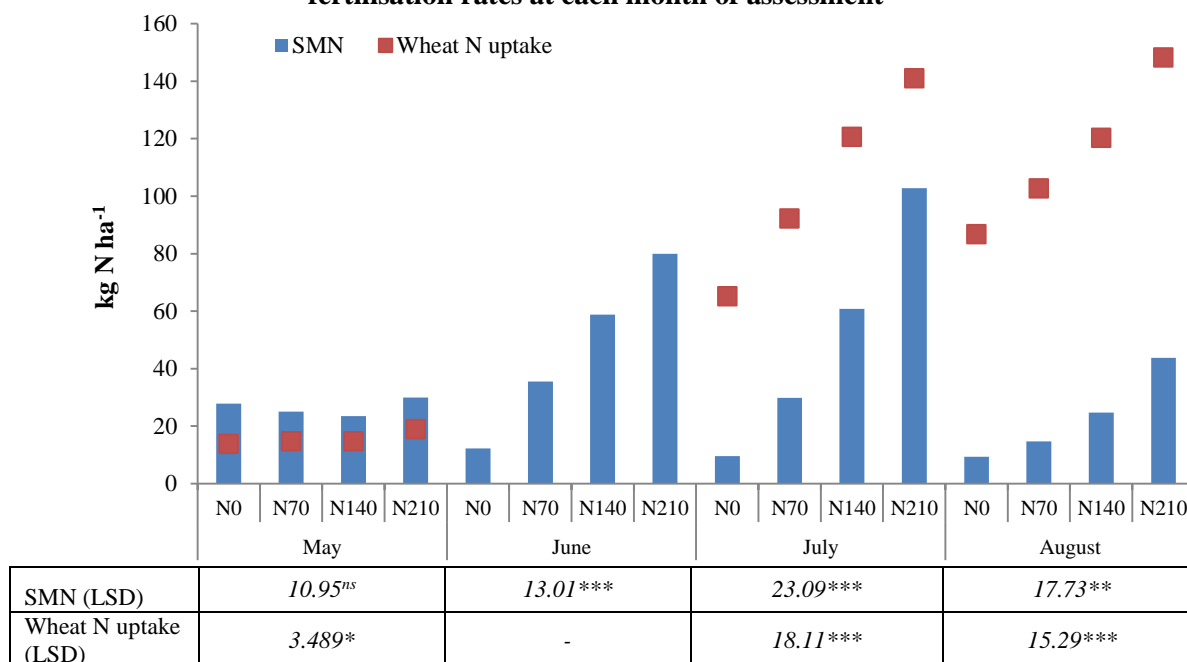
LSD at *P*<0.05 at each month of assessment; *= *P*<0.05; ***= *P*<0.001; and ns= no significant

5.3.10. Soil moisture (gravimetric) content

Soil moisture content was relatively stable across spring months when rainfall was higher than the long-term seasonal average (Figure 5.31). However, moisture content level decreased in July as a result of the warm and dry weather conditions experienced.

Throughout the assessment months, cultivation techniques only significantly affected soil moisture content in April, when CT resulted in lower moisture content than HINiT and LINiT (Figure 5.31). No significant effect of N fertilisation and undersowing treatments were observed at any assessment time.

At the June assessment, due to significant interactions, moisture content was significantly higher under N0 with LINiT than with HINiT and CT. LINiT resulted in higher moisture content with N70, specifically compared with CT. No significant differences were observed between cultivation techniques with N140 and N210 rates (Figure 5.32). At the August assessment, HINiT resulted in higher soil moisture content particularly than LINiT under Nus (Figure 5.33).

Figure 5. 31. Effect of cultivation techniques and nitrogen fertilisation on soil gravimetric moisture content (%) with mean precipitation during the 2014 experimental period in comparison to the 10-year average
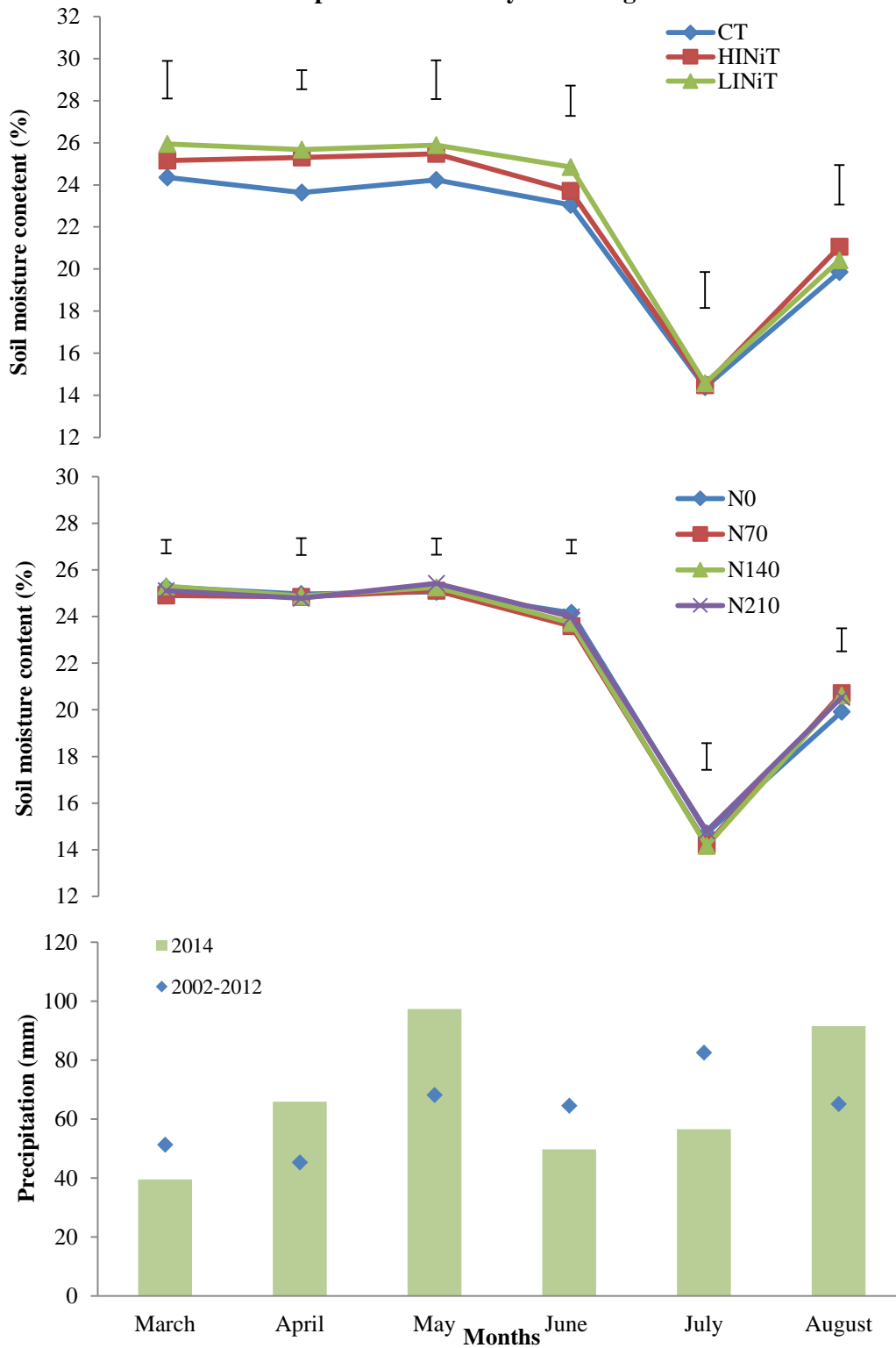
Error bars representing LSD (*P*<0.05) at each month of assessment

Figure 5. 32. Cultivation techniques and nitrogen fertilisation interaction effect on soil moisture content (%) (June 2014)
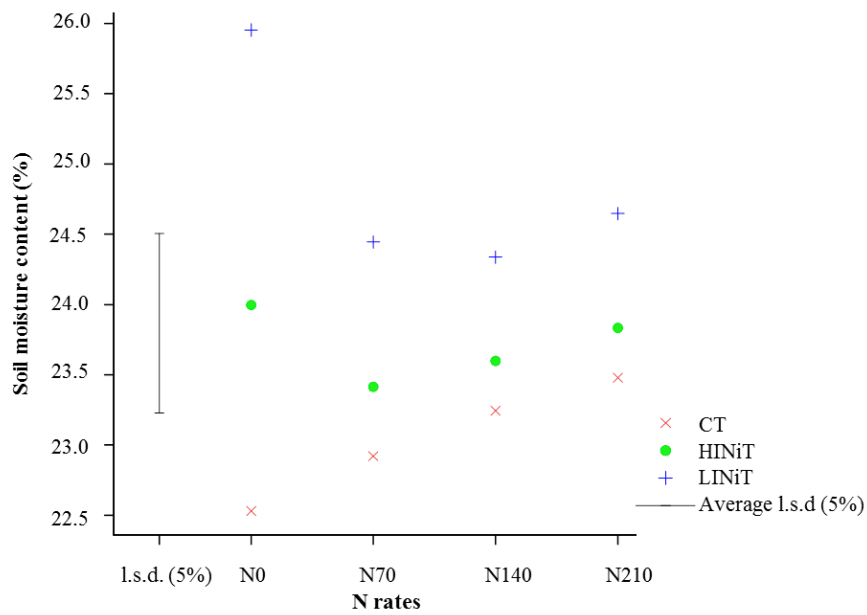
Error bars representing LSD (*P*<0.05)

Figure 5. 33. Cultivation techniques and undersowing interaction effect on soil moisture content (%) (August 2014)
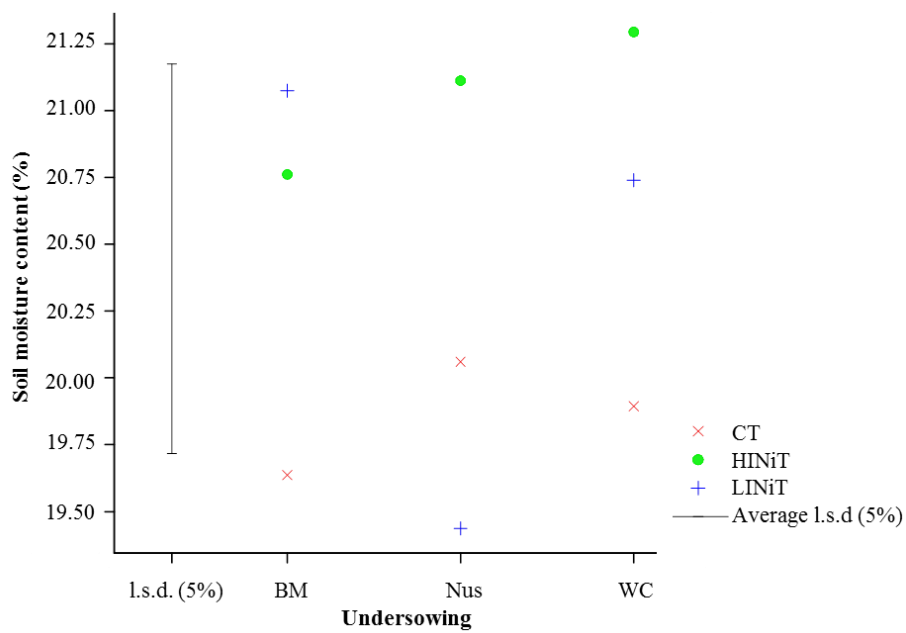
Error bars representing LSD (*P*<0.05)

5.3.11. Soil pH

Soil pH was only measured in March 2014 in order to evaluate initial values for the cropping season. Overall soil pH was 7.0 and was not significantly affected by any treatment structure or interactions. No further measurements were carried due to no significant effect observed in 2013 cropping. The N fertilisation effect observed in 2013 was only temporal.

5.3.12. Soil penetration resistance

Soil penetration resistance after cultivation techniques operations (March 2014), during vegetative growth (June 2014), and before harvest (August 2014) were not significantly affected by tillage treatments. In addition, in all assessments time, soil penetration resistance was lower than 2MPa which is the upper limit for root restriction growth (Atwell, 1993). Nevertheless, penetration resistance showed a depth gradient effect. In the April and June assessments, penetration resistance was higher at 30cm depth compared with above soil layers (at 5cm, 10cm, and 15cm) (Figure 5.34 & 5.35).

Figure 5. 34. Effect of cultivation techniques and soil depth interaction on soil penetration resistance (kPa) (March 2014) with cultivation techniques soil disturbance depth
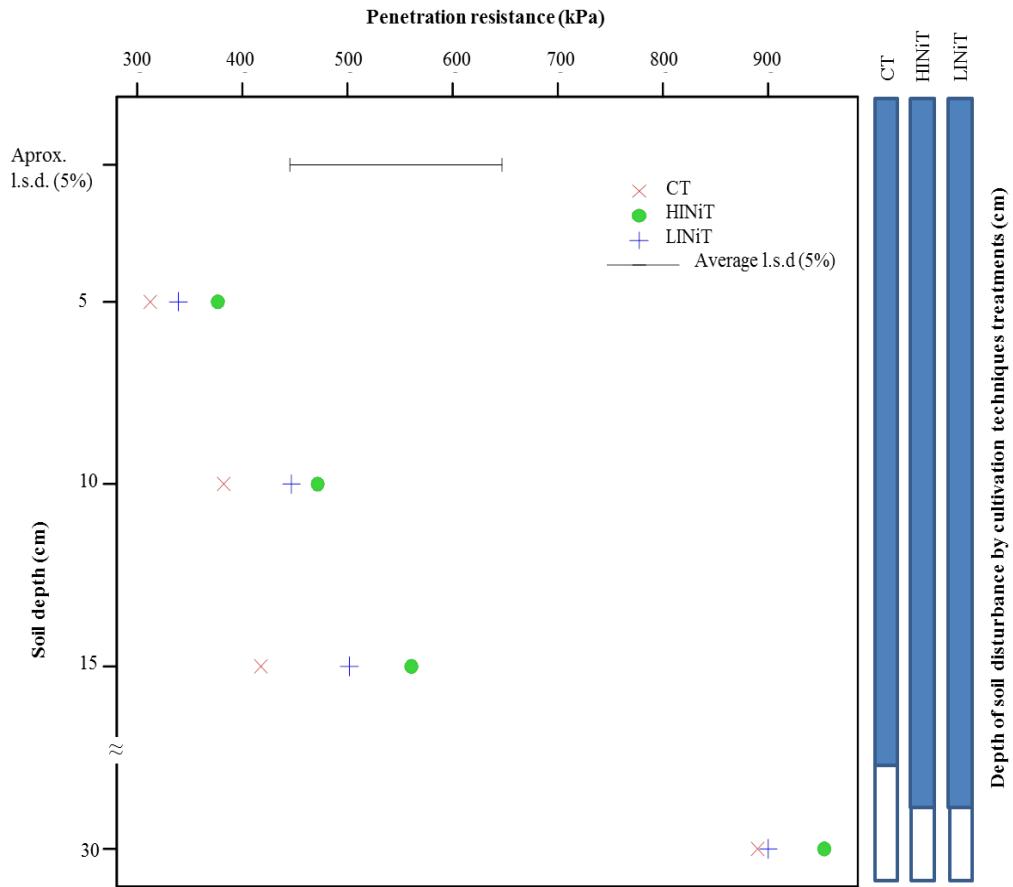
Error bar represents average LSD value at *P*<0.05

Figure 5. 35. Effect of cultivation techniques and soil depth interaction on soil penetration resistance (kPa) (June 2014) with cultivation techniques soil disturbance depth

Error bars representing LSD (*P*<0.05)
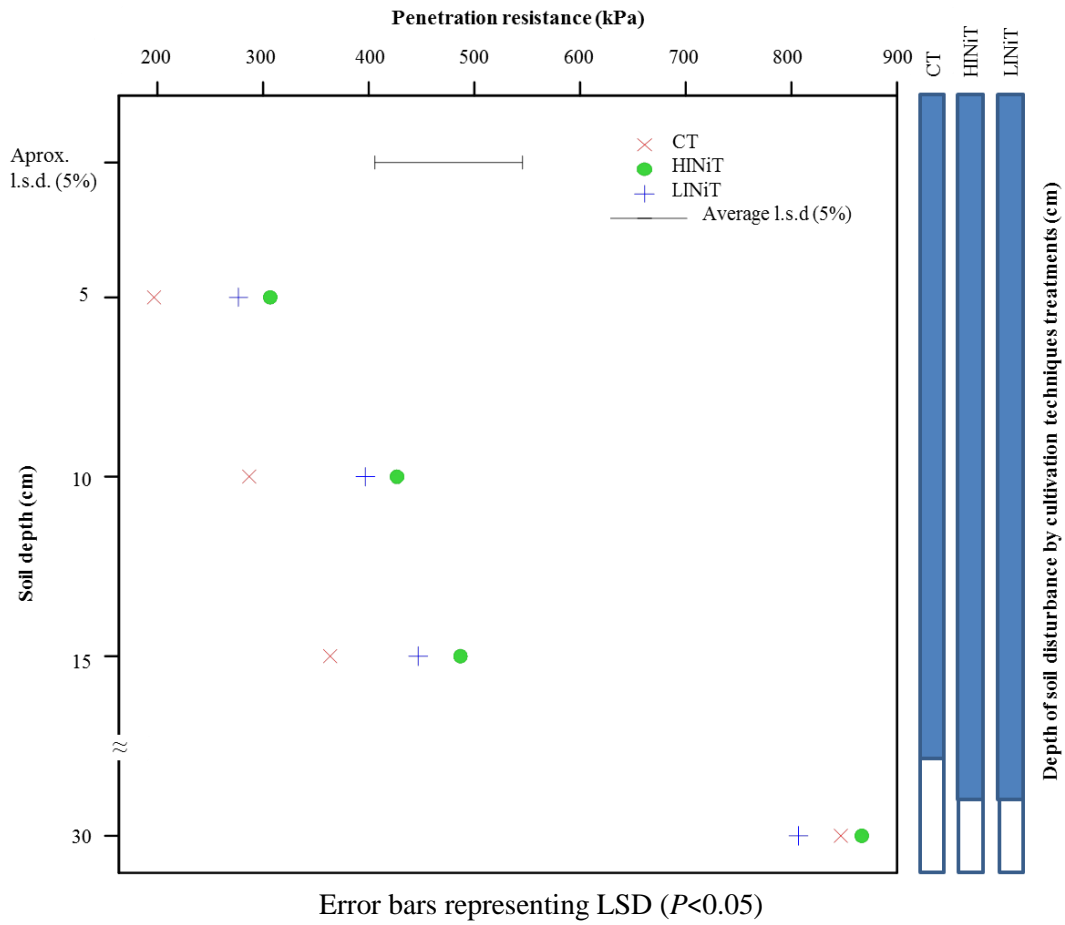
In August, soil penetration resistance was lower at 5cm than 10cm and 30cm while no significant differences were observed between 15cm and 30cm depth (Figure 5.36).

Figure 5. 36. Effect of cultivation techniques and soil depth interaction on soil penetration resistance (kPa) (August 2014) with cultivation techniques soil disturbance depth

Error bars representing LSD (*P*<0.05)
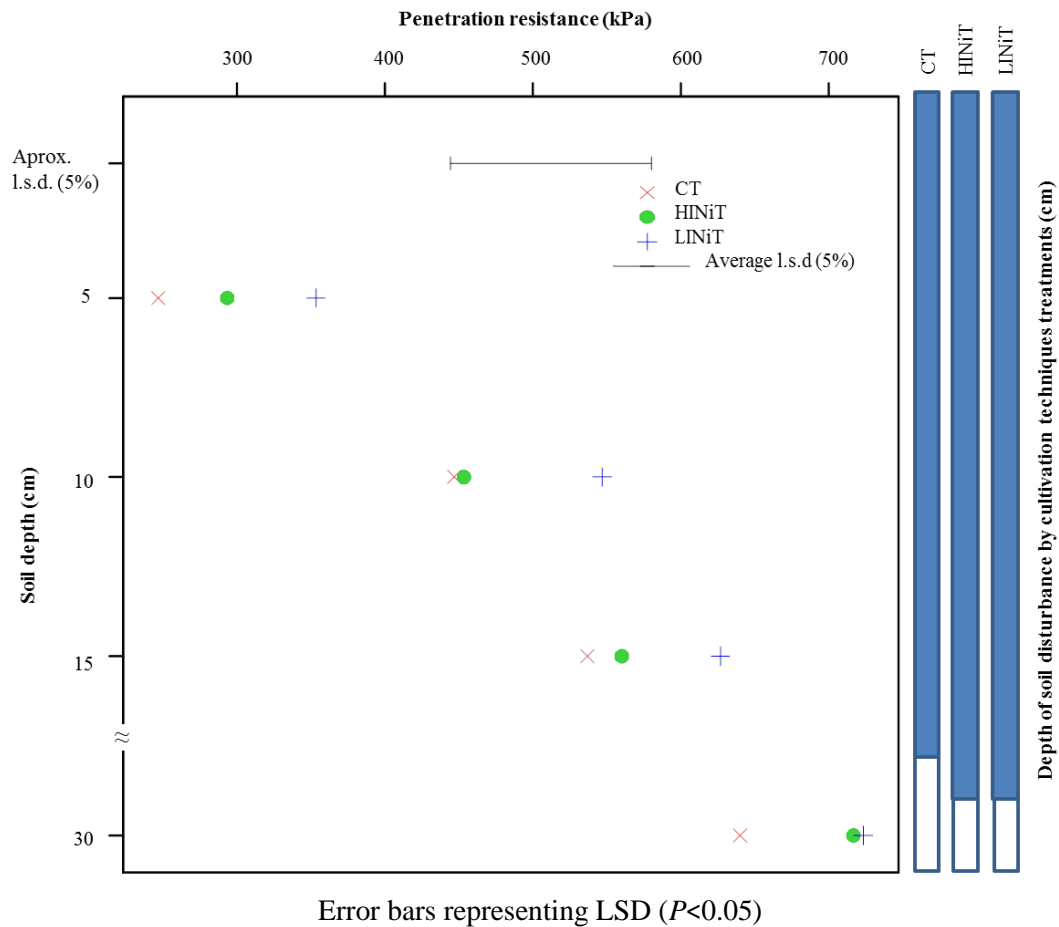
5.4. Discussion

5.4.1. Overwinter growth assessment

In the 2013 cropping season, the undersown legume species had poor and low establishment, and slow growth. However after the 2013 harvest, the legume species undersown were allowed to grow during winter, resulting in higher legume DM under CT than non-inversion tillage systems, as also observed at the 2013 harvest time. Nevertheless, the overwinter legume DM was higher than the biomass recorded at harvest 2013, supporting the observation that the undersown legume species have slow growth but great biomass production and winter hardiness, as reported by others (Döring *et al*., 2013; Jones, 1992; Smýkal *et al*., 2015). Lower legume DM observed under LINiT was probably an effect of the increased weed biomass observed under this

treatment compared with CT and HINiT. This suggests that weed growth was more favourable under LINiT during winter time, perhaps due to higher weed seeds in the soil surface, germinating later in in the season.

The greater weed DM under high N fertilisation rate treatment suggests that, regardless of the lower soil residual N level, weed N uptake competitiveness allows their growth, as also reported by Bergkvist (2003). However, the greater legume biomass and higher N uptake under unfertilised conditions corroborate that legume species can be more competitive under low N environments due to their capacity to fix N, and to produce great biomass which possibly reduces weed pressure. This supports Döring *et al.,* (2013) and Liebman & Dyck (1993) reporting that a weed suppression efficiency by a cover crop is mainly dependant on its biomass production. Increasing N supply may have reduced legumes competitiveness against weeds, resulting in higher weed N uptake under BM than with WC under N supply conditions. Döring *et al*., (2013) and Squire (1997) suggested that BM produces lower biomass than WC which can negatively result in lower competitiveness against weeds.

5.4.2. Soil penetration resistance

According to Atwell (1993), soil penetration resistance higher than 2 MPa can disrupt root growth and adversely affect crop development. In the present study, penetration resistance at all assessment times and at any soil depth measured (up to 30 cm depth), seems to have no restrict root growth as it was lower than 2 MPa. Increasing penetration resistance was observed specifically when the first 15cm of soil was compared with the 30 cm soil depth layer, agreeing with other authors reporting a depth gradient (Grant & Lafond, 1993; Martinez *et al.,* 2008). In the present study, cultivation techniques did not significantly affect soil penetration resistance at any soil depth layer, in contrast with findings by other studies (Ardvisson *et al.,* 2013; Carter *et al.,* 1965; López-Bellido *et al.,* 1996).

5.4.3. Plant establishment, tillers and total shoot production

In the temperate climate of the UK, spring wheat has a relatively short growing season making necessary an early sowing in spring in order to the crop to produce an adequate crop canopy (Webb *et al*., 1995). However, UK weather conditions are not always suitable for early sowing. High rainfall in April 2014 delayed spring wheat drilling operations, which probably negatively affected plant establishment. This resulted in fewer plants established, perhaphs, compared with the 2013 season. Variations of tillage intensity influenced seedbed conditions affecting the crop establishment, growth and development (Strudley *et al.,* 2008). Increasing soil disturbance and reducing soil residues cover under CT and HINiT resulted in higher plant establishment, as also reported by Arvidsson *et al.* (2014). Less soil movement and the higher presence of wheat stubbles under LINiT produced a coarse seedbed. This may have affected seed-soil contact, reducing the crop establishment, as reported by others (Graham *et al*., 1985; Känkänen *et al.*, 2011; Pietola & Tanni, 2003).

Tiller production is cultivar-dependant, but it can be modified by growing conditions and management operations (Peltonen-Sainio *et al.,* 2009). Cultivation techniques that affected plant establishment also influenced the number of tillers produced, with CT and HINiT having significantly higher tillers per unit area than LINiT. High crop residue retention in the soil surface under non-inversion tillage systems can affect soil conditions by reducing evaporation limiting soil temperature fluctuations, as reported by Morris *et al.*, (2011) and Reicosky *et al*. (1995). These conditions could perhaps have created cold soils under the non-inversion tillage systems and have adversely affected the onset of tillers, giving lower number of shoots compared with CT, as reported elsewhere by Rasmussen *et al.* (1997). In addition, increasing weed pressure under non-inversion tillage could have adversely affected shoot production in spite of the greater tillers number under HINiT.

Contrary to several authors (Cannell, 1985; Power & Alessi, 1978; Otteson *et al.,* 2008; Weisz *et al.*, 2001), in the present study, application of N fertiliser did not significantly affect crop establishment and early crop development.

5.4.4. Mid-season plant biomass and nitrogen uptake

5.4.4.1.Wheat

Cultivation techniques effects

Cultivation effects on initial crop establishment and early crop development seem to also have significantly affected the mid-season crop growth. In May, maximum tillage intensity under CT resulted in higher wheat DM, probably as a result of the high plant establishment and the increased tiller production compared specifically with LINiT. Although, HINiT treatment resulted in statistically similar establishment and tiller production than CT, wheat DM was lower when compared with ploughed plots. This was possibly as the soil cover produced a colder soil environment slowing down wheat biomass growth, as widely reported (Alakukku *et al.,* 2009; Bahrani *et al.,* 2007; Känkänen *et al*., 2011). This was also evident as shoot number decreased under non-inversion tillage, probably accounting for the low wheat biomass production at the July and August assessments. Decreasing soil disturbance resulted in higher variability of seedbed conditions and greater weed pressure under non-inversion tillage, negatively affecting crop growth compared with CT across the mid-season growth assessments.

Intensifying soil disturbance by cultivation operations can often increases SMN content mainly by exposing organic matter to decomposition, as reported by Myrbeck *et al*. (2012) and Silgram & Shepherd (1999). Maximum soil disturbance and incorporation of plant residues into the soil under CT resulted in higher availability of N allowing greater N uptake by the crop, compared with non-inversion tillage across the cropping season. However, at the early assessments similar SMN levels between cultivation treatments suggests that higher wheat N uptake under CT than HINiT followed by LINiT, was likely to be related to plant establishment rather than influenced by the soil N availability. This agrees with Brennan *et al.* (2014) reporting that lower plant population results in less N uptake. Differences between non-inversion tillage treatments on wheat N uptake were less evident later in the season (July and August), suggesting that N availability reduced the initial differences as soil N levels were statistically similar.

Nitrogen fertilisation effect

For cereal plant growth there is an absolute requirement of N, although growth rate depends on N inputs and timing between N supplies and crop N demand (Justes *et al.,* 1994). However, wheat N and biomass accumulation depend on intra-regulation of crop physical processes (Gastal & Lemaire, 2002). During early growth assessment, N fertilisation significantly increased total wheat N uptake. It did not increase wheat DM, however, as no significant differences between N treatments were observed, as also found by Qiao *et al.* (2013) at an early crop growth stage. Conversely, at later growth assessments, the wheat DM production was significantly affected by N fertilisation treatments, although differences between N rates were more evident later in the season (August). Wheat DM in August significantly increased with 210 kg N ha^{-1} applied, particularly compared with unfertilised plots, while N140 and N70 resulted in similar wheat DM. This was also observed by López-Bellido *et al.* (2005) and Pearman *et al.* (1977) who reported increases in crop biomass production with increasing N fertilisation supply. At this growth stage the crop was reaching its maximum growth under high N conditions (Justes *et al.,* 1994), but a similar N availability under N140 and N70 plots possibly triggered comparable wheat biomass production. In addition, increases of total wheat N uptake with increasing N fertilisation rate probably promoted differences in wheat biomass growth between high N rate treatments and unfertilised conditions, as also reported by others (Power & Alessi, 1978; Justes *et al*., 1994; van Keulen & Seligman, 1987).

Interaction effect

At early crop growth the WC undersown significantly encouraged wheat N uptake compared with Nus and BM with the application of 210 kg N ha^{-1}. In July, WC and Nus resulted in higher crop N uptake under CT. The slow growth pattern of WC and its lower competitiveness under N-rich conditions (Moss *et al*., 2004) possibly allowed more N for the crop and increased N uptake.

5.4.4.2.Legumes

Despite delayed wheat sowing, the environmental conditions in May 2014 were expected to be favourable for establishment and growth of the undersown legume species. Within a week after legume broadcast, however, the average air temperature and rainfall were 13.7°C and 1.7 mm. Such dry (1.7mm vs 97.30mm average in May 2014) and still warmer (13.7°C vs 12.8°C, average in May 2014) conditions were unfavourable for the legume species to germinate and establish, as also observed in the 2013 cropping season. This may have resulted in low legume DM during all growth assessments and perhaps triggered the lack of undersowing effect in a wide range of assessments.

Nitrogen fertilisation effect

In May and August higher wheat and weed biomass growth possibly reduced legume DM when N fertilisation was applied. This is the result of poor competitiveness of BM and WC under N-rich conditions, as reported by other authors (Döring *et al.,* 2013; Elgersma *et al.,* 2000; Gooding & Davies, 1997; Moss *et al.*, 2004; Soussana & Arregui, 1995).

Interaction effect

At the overwinter assessment, increasing tillage intensity resulted in higher legume DM as a result of lower weed competition. After herbicide applications, however, legumes that survived broad-spectrum herbicide application were incorporated into the soil under CT resulting in lower legume DM. In contrast, lower tillage intensity under non-inversion tillage increased legume biomass. This combined with less SMN content under HINiT than LINiT, favoured legume species growth, as observed in May and August. This agrees with Carr *et al.,* (2004), who reported higher total aboveground legume DM in soils with low N content compared with high N soil conditions.

5.4.4.3.Weeds

As for the 2013 cropping season, weed species observed during the 2014 season are commonly report in UK spring wheat (HGCA, 2010a) and their presence was again influenced by the agricultural management treatments and assessment date.

Herbicide application prior to cultivation operations appears to have provided a good head-start for the main crop, allowing its faster growth. It possibly contributed to reduced weed biomass production and mitigated any treatment effect in the early growth assessment (in May). This was more evident with grass weeds as the herbicide application seems to have particularly reduced their growth across the cropping season.

Cultivation techniques effect

In July and August, decreasing tillage intensity under non-inversion tillage led to higher total weed biomass compared with CT, as also reported by several authors (Cardina *et al.,* 1991; Clements *et al.* 1994a; Clements *et al*., 1996a; Swanton *et al*., 2000). In the present study, broadleaf weed species were the main contributors to total weed DM under non-inversion tillage. Weeds retained in soil under HINiT could have germinated after the herbicide application. Soil movement without soil inversion under HINiT, therefore, allowed more short-lived broadleaf weeds than CT and LINiT, as also observed in the 2013 cropping season. The high biomass of *Sinapsis arvensis* L. and *Stellaria media* L. under HINiT suggest their great contribution to total weed DM. These species accounted for 50.3% of the total weed biomass observed at the July assessment. This agrees with Ozpinar (2006) who reported the higher presence of *Sinapsis arvensis* under reduced tillage compared with CT. However, maximum reduction of tillage intensity under LINiT resulted in greater soil residues cover, creating shading and negatively affecting broadleaf weeds that survive herbicide application, as reported by other studies (Johnson *et al*., 1993; Streit *et al*., 2002; Teasdale *et al*., 1991). Subsequent soil inversion after the foliar-contact herbicide application and greater crop competitiveness against weeds appear to have reduced broadleaf weeds biomass under CT, as observed by several authors (Demjanová *et al.*, 2009; Gruber *et al.,* 2012; Menalled *et al*., 2001; Vijaya Bhaskar *et al.,* 2014b). Higher

weed N uptake under non-inversion tillage suggests that N uptake was a result of the greater weed DM under those treatments, rather than the soil N availability.

Nitrogen fertilisation effect

Total weed biomass was affected by N application, confirming that weed growth responds positively to higher N levels, as also reported by Blackshaw *et al*. (2005). Increasing broadleaf biomass was observed under N fertilised conditions compared with unfertilised plots, while grass weeds were not significantly affected. This confirms N supply differentially affects weed species growth, and can modify the competitive interactions between species (Iqbal & Wright, 1997). The dominant weed species, *Sinapsis arvensis* and S*tellaria media* contributed to the greater weeds biomass under N application rates, as these species seems to be highly more competitive under N-rich conditions (Iqbal & Wright, 1997; Moss *et al*., 2004; Lal *et al.,* 2014). Weed N uptake, at the July and August assessments, was affected by N fertilisation treatments with N0 resulting in the lowest N weed uptake. This indicates that weed N uptake increased with increasing N supply as also observed on weed biomass, agreeing with Blackshaw *et al*. (2005) findings.

Undersowing effect

The increased competitive behaviour of *Stellaria media* under N-rich conditions (Moss *et al*., 2004; Parchoma, 2002) possibly encouraged its biomass growth under WC as SMN was higher, particularly under N210 treatment.

Interaction effect

Cultivation techniques and N fertilisation interacted affecting weeds DM. N application under non-inversion tillage resulted in higher broadleaf and total weed biomass at the July and August assessments. HINiT increased *Sinapsis arvensis* biomass when N fertiliser was applied, regardless of the N rate. This support preference of this broadleaf weed species to N fertile conditions (Lundkvist & Verwijst, 2011). *Sinapsis arvensis* DM also positively responded to N70 and N210 applications under HINiT with WC undersown and Nus. However, when N140 was applied under HINiT, BM undersown resulted in higher *Sinapsis arvensis* DM. *Sinapsis arvensis* is more advantaged under

non-inversion tillage (Streit *et al.,* 2003), therefore, and its competitiveness was higher than the undersown legume species under N-rich conditions, particularly BM as this species has low biomass production and is disadvantageous to high N supply (Moss *et al.*, 2004).

5.4.5. Plant height and ears number

Cultivation techniques effect

As also observed in the 2013 cropping season, cultivation treatments did not significantly affect wheat plant height, indicating that weather conditions and N management were more relevant. Nevertheless, average plant height was relative shorter than in the 2013 cropping season, regardless of treatments. This is probably a result of later sowing, as the crop growth over a shorter period (Prasad *et al.*, 2008).

Tillage management affecting plant establishment, tiller production and shoot survival can also influence ear production (Mc-Master *et al.*, 1994). Soil conditions under CT were favourable for wheat growth promoting tillers and shoot production, and later greater number of ears per area (López-Bellido *et al.,* 1998; López-Bellido *et al.,* 2000). Similarly, Brennan *et al.* (2014) reported that high crop establishment under CT can contribute to high ear production. However, LINiT resulted in variable seedbed conditions and higher weed pressure compared with CT, inducing slower plant growth, affecting shoot survival and final ear number (Boomsma *et al.*, 2010). Higher tillage intensity and higher soil cover under HINiT could have resulted in similar ears number with LINiT and CT.

N fertilisation effect

Increases in plant height with increasing N supply is a well-known result of increasing N availability (Alijani *et al.*, 2012; Sourour *et al.*, 2014) and promoting the early vigorous wheat growth (Ayoub *et al.,* 1993; Lloveras *et al.,* 2001) by N fertilisation, particularly with high application rates, N140 and N210 in the present study.

Contrary to Abad *et al*. (2005) and Hay & Walker (1989) reporting increases in ear number by N fertilisation due to more tillering, the present study showed that N fertilisation did not significantly affect tillers production or ears number per area.

Interaction effect

Taller plants were observed in CT than LINiT and HINiT under unfertilised conditions. Suggesting that tillage treatment effects on nutrient availability promote plant growth as higher SMN level was recorded under CT, compared with non-inversion tillage treatments, as observed by Alijani *et al.* (2012).

Under BM undersown and Nus, CT resulted in higher ears number compared with non-inversion tillage treatments. While under WC, CT specifically resulted in higher ears number than LINiT. The higher wheat N uptake, observed at the July assessment, may have encouraged shoot survival and promoted more ears under those treatments interactions. Abad *et al.* (2005) also reported a positive effect on shoot survival and ears number with increasing wheat N uptake.

5.4.6. Ear, straw and total wheat biomass

Cultivation techniques effect

Under CT, higher ears number and the greater promotion of crop growth resulted in higher total wheat DM, compared with non-inversion tillage treatments. Greater variability of seedbed conditions and higher weed pressure observed under non-inversion tillage induced slower plant growth and ears number than CT resulting in poor total wheat DM, as observed by Boomsma *et al.* (2010) and Mehdi *et al.* (1999).

Nitrogen fertilisation effect

Increases in the early wheat biomass production by N fertilisation were translated to the final straw DM, with higher biomass with increasing N supply. The promoting N fertilisation effect on ear DM was a result of increasing number of grains per ear rather than an increase in the ears number per unit area, as previously reported by Pearman *et al*. (1977).

Under BM, CT resulted in higher straw DM than LINiT, followed by HINiT. While CT with WC and Nus, resulted in higher straw DM compared with non-inversion tillage systems. These significant interaction effects on straw DM may have been triggered by the increase of earlier wheat N uptake previously discussed.

5.4.7. TGW, grains per ears, final grain yield and harvest index

Cultivation techniques effect

Differences in agricultural management, weather conditions, weed pressure and N availability influenced crop growth and final grain yield between cultivation techniques treatments. Higher plant establishment and plant growth followed by significantly higher ears number and grains per ear resulted in a significantly higher yield under CT than non-inversion tillage systems, regardless of the statistically similar TGW. In contrast, the higher variability of seedbed conditions combined with higher weed presence and lower N availability under non-inversion tillage systems negatively affected early crop growth and development. These negative constraints under non-inversion tillage resulted in less plant established and low plant growth followed by low ear number and grains per ear, finally causing a lower grain yield than CT. Several authors (Alvarez & Steinbach, 2009; Arvidsson *et al*., 2013; Brennan *et al*., 2014; Franchini *et al.,* 2012; López-Bellido *et al.,* 2000; Pietola, 2005; Vijaya Bhaskar *et al.,* 2013b) also reported higher yields under CT as with more favourable growing conditions compared with non-inversion tillage systems.

The higher number of grains per ear under CT followed by LINiT perhaps triggered similar harvest index (HI) under these treatments, as also reported by Hay (1995). However, it is evident that the higher total wheat DM under CT supported a higher grain yield compared with non-inversion tillage.

Nitrogen fertilisation effect

Thousand grain weight (TGW) is genetically determined, although its expression is affected by growing environment (De Vita *et al.,* 2007; Mogensen *et al.,* 1985). In the present study, increasing N fertilisation rate decreased TGW, although N70 and N140 resulted in statistically similar TGW. Lower TGW probably resulted from higher number of grains per ear and lower grain fill, perhaphs, as reported by other authors (Alijani *et al.,* 2012; López-Bellido *et al.,* 2000; Pearman *et al*., 1977; Rasmussen *et al.,* 1997).

Increasing N availability when 140 and 210 kg N ha^{-1} were applied promoted higher number of grains resulting in significantly higher final grain yield. Several authors (Abad *et al.,* 2005; Alijani *et al.,* 2012; Halvorson *et al.,* 2001; Wang *et al.,* 2014) also reported a positive crop yield response with mineral N fertilisation.

Interaction effect

Non-inversion tillage resulted in more grains per ear when N140 and N210 were applied. These interactions suggest that the lower soil N availability under non-inversion tillage negatively affected grain production, making a higher N supply necessary to increase grains number per ear. This agrees with McConkey *et al.,* (2002) reporting that non-inversion tillage can require higher N supply to increase grain number compared with CT.

Cultivation techniques and undersowing treatments interaction effects on HI was strongly related to their effect on straw biomass. LINiT resulted in higher straw DM under BM specifically than Nus, reducing the HI under these treatments interactions.

5.4.8. Wheat N yield, grain protein and N efficiencies

Protein content in the present study was slightly lower compared with 2013 spring wheat. This might be due to interactions between environmental conditions (perhaps higher rainfall) and lower grain yields. These well-known observations support several authors (López-Bellido *et al.,* 1998 & 2001; Rao *et al.*, 1993; Stobard & Marshall,

1990) reporting that grain protein is highly determined by genotype, although still influenced by prevailing environmental conditions. This was evident with grain protein content not being significantly influenced by cultivation treatments, in spite of higher total wheat and grain N uptake under CT.

Cultivation techniques influences on SMN levels, final grain yield and N uptake seem to result from variations of N-use efficiency (NUE) and N-uptake efficiency (NUpE), as also reported by Håkansson (1994). Higher N availability, total wheat N-uptake and final crop yield under CT led to higher NUE and NUpE than with non-inversion tillage systems.

Nitrogen fertilisation effect

High N rate treatments significantly increased total wheat and grain N uptake compared with low N rate – the N70 and unfertilised conditions, indicating greater N availability at the time of crop high demand as reported by Campbell *et al.* (1977) and Halvorson *et al.* (2001). In the same way, higher grain protein content was also observed under N210 than N140, followed by N70 and N0, as reported by other authors (Garrido-Lestache *et al.,* 2004; Godfrey *et al.,* 2010; López-Bellido *et al.,* 2001). However, application of N fertiliser at 210 kg N ha^{-1} would appear to be only justified for improving grain protein content, as this rate did not increase grain yield compared with 140 kg N ha^{-1} application.

NUE and NUpE decreased with increasing N rate, probably as a result of increasing N supply increasing aboveground N relative to grain yield, as also reported by Huggins *et al.,* (2010). However, N utilisation efficiency (NUtE) was significantly lower under N210 compared with any other N rate, suggesting lower efficiency in the use of the total wheat N uptake to produce the final yield. This was corroborated as N210 resulted in the highest total wheat N uptake, while grain yield was similar to that of N140.

5.4.9. Non-wheat biomass and N yield at harvest

5.4.9.1.Weeds

Weed biomass was reduced from the mid-season assessments to harvest time, probably as a result of natural decay of the weeds and warm and dry conditions during the summer. This was also observed during the 2013 cropping season.

Cultivation techniques effect

As previously observed during the mid-season growth assessments, seedbed conditions under non-inversion tillage treatments also resulted in high weed biomass at harvest time. The increase in tillage intensity and the soil inversion under CT resulted in less weed pressure, also favouring wheat growth and increasing wheat competitiveness against weeds, as also reported by Håkansson (2003) and Swanton *et al.* (2000). Lower N availability under non-inversion tillage suggests that the higher weed N uptake under these treatments was triggered by increases in weed DM, rather than by the soil N available.

Nitrogen fertilisation effect

Mineral N fertilisation affects soil fertility, influencing not only the main crop growth but also weeds growth (Jornsgård *et al.,* 1996; O'Donovan *et al.,* 1997). As also observed at the mid-season assessments, N application significantly increased weed pressure compared with unfertilised plots. Several authors (Ampog-Nyarko & De Datta, 1993; Blackshaw *et al.,* 2005; Moss *et al*., 2004; Lal *et al.,* 2014) also reported a positive weed growth and N uptake response to N fertilisation, mainly due to differential competitiveness to N supply by the various weed species.

5.4.9.2.Legumes

Poor establishment of the undersown legume species resulted in low legume DM across the cropping season, regardless of management treatments. However, higher legume DM at harvest time compared with the mid-season assessments reinforces, as also observed in the 2013 season, the slow growth pattern but greater biomass production of

BM and WC (Döring *et al*., 2013). Similarly, Amossé *et al.* (2013) reported that legume cover crops established under winter wheat can reach high levels of biomass at harvest time. Nevertheless, later legume growth was not significantly related to cultivation techniques and N fertilisation treatments, although unfertilised treatment resulted in higher legume N uptake. This emphasised the low response of legume species under fertile N conditions (Döring *et al*., 2013). Higher legume biomass and N uptake under BM compared with WC and Nus agree with Döring *et al*., (2013) reporting that BM aboveground biomass is significantly higher than WC, regardless of the slow establishment of BM (Wallace, 2001). However, Nus resulted in similar biomass than WC which perhaps is a result of natural regeneration of the legumes, in spite of previous herbicide application. Under Nus, legumes were separated from weeds even though they were considered legume weeds rather than the intended undersown legume.

5.4.10. Soil moisture content

Soil moisture content is highly affected by weather conditions and by soil management practices adopted (Fitter, 1991). In the present study, soil moisture (gravimetric) content seems to be fairly consistent across spring months. This is probably the result of increasing rainfall from March to May, which coincided with fast crop growth. Increasing crop growth increases demand for water, affecting moisture content level (Pietola & Tanni, 2003). Later crop growth combined with low rainfall and high temperatures during the summer months, however, resulted in a decline of moisture content in June which was highly evident in July. In contrast, increasing rainfall in August increased the soil moisture content.

Cultivation techniques effect

Cultivation techniques affected soil moisture content although this was only significantly evident in April, when CT resulted in lower moisture content compared with non-inversion treatments. Land preparations at the end of March and crop sowing in mid-April probably created differences between cultivation techniques. Maximum soil disturbance under CT breaks the water-related pores increasing water loss by evaporation (Reicosky *et al.,* 1999). In contrast, less soil disturbance and greater soil

residues cover under non-inversion tillage treatments reduce evaporation and run-off while also slowing soil drying (Baumhardt & Jones 2002; Beyaert *et al.,* 2002; Steiner, 1989). These attributes under non-inversion tillage treatments maintain or perhaps increase soil moisture content, as also reported by others (Fabrizzi *et al,.* 2005; Hatfield et *al.,* 2001; Pietola, 2005).

5.4.11. Soil mineral nitrogen

Soil mineral nitrogen (SMN) content in March 2014 was lower than the residual SMN observed after 2013 harvest. Despite the fact that no leaching assessment was performed, the low SMN content in March 2014 was thought to be the result of N losses by leaching and/or denitrification due to high rainfall occurring during winter months. Several authors (Abad *et al.,* 2005; Halvorson *et al.,* 2001; Lloveras *et al.,* 2001) have also reported decreases in residual SMN content as expected following high rainfall leaching soil N. Additionally, overwinter assessments showed that legumes and weed N uptake could have also contributed to reductions of SMN.

Cultivation techniques effect

Soil disturbance often increases SMN content as organic matter is exposed to decomposition, although such an effect is reportedly temporary (Myrbeck *et al*., 2012; Silgram & Shepherd, 1999). In the present study, the cultivation techniques treatments only affected SMN content from June until August. At the June assessment, CT resulted in higher SMN than LINiT, followed by HINiT. Maximum soil disturbance with CT can greatly increase organic matter mineralisation increasing SMN to meet crop N demand, as widely reported (Gruber *et al.,* 2011; McConkey *et al*., 2002; López-Bellido *et al*., 2013; Soon *et al*., 2001; Yagioka *et al*., 2015). Less tillage intensity and soil cover presence can result in slow decomposition of crop residues and high N immobilisation or low rate of N releases. This can, therefore, result in lower SMN under non-inversion tillage than under CT, agreeing with several authors (Alvarez *et al*., 1995; López-Bellido *et al*., 2013; López-Bellido *et al*., 1997). In addition, the reduction of tillage intensity, higher plant establishment and early plant growth under HINiT probably resulted in lower SMN level than CT and LINiT at the June assessment. Nevertheless,

later in the season (in July and August) CT continued to present higher SMN levels than non-inversion tillage in spite of higher plant biomass production (and N uptake). This may have been the result of increasing mineralisation and low N losses with high temperatures and low rainfall recorded in these months.

SMN availability and root distribution determine plant N uptake (Gastal & Lemaire, 2002). Greenwood *et al*. (1990) suggested that N uptake has often related either to crop demand or to soil N availability rather than both simultaneously. Throughout the present assessments, total wheat N uptake was higher under CT compared with non-inversion tillage treatments. This suggests that maximum soil disturbance increased SMN, and promoted better crop growth and productivity compared with reductions in tillage intensity, as also reported by Germon *et al*. (1994). Differences between cultivation techniques on wheat N uptake in the May assessment, despite SMN content being unaffected by tillage treatments, suggests that N uptake at this time was induced by differences in plant population levels affecting total wheat biomass.

Nitrogen fertilisation effect

Application of N fertiliser in late May seems to increase SMN levels even though this started to be evident in June rather than in May. This resulted from earlier soil assessment in May before the N applications. Similarly, several authors (Giacomini *et al.,* 2010; Glendining et al., 1996; Liebig *et al.,* 2002; Zhao *et al.,* 2014) reported increases in SMN content with increasing N fertilisation supply. In the present study, the application of 210 kg N ha^{-1} resulted in high SMN content from June till August. Howerver, increases in wheat N uptake across growth assessments seem to have reduced differences between the low N rates as a result of increasing crop N demand as the crop approached maturity (Fuente *et al.,* 2003). This possibly depleted SMN levels when N supplies were low, agreeing with Zhao *et al.* (2014) reporting reductions of SMN content when crop uptake is higher than the N supplied.

Interaction effect

At the July assessment, cultivation techniques did not affect SMN content when there was a deficiency of N (N0 and N70). Differences were only evident at high N rates (N140 and N210) when SMN contents were higher under CT than under non-inversion

tillage, specifically HINiT. Similarly, López-Bellido *et al*. (2013) also reported higher SMN level under CT compared with non-inversion tillage when high N rates were supplied. At the August assessment, significantly higher legume N uptake under BM at harvest time perhaps reduced SMN. This was probably the effect of CT significantly interacting with BM and Nus, resulting in lower SMN content compared with the undersown WC.

5.5. Conclusions

Delayed sowing, variations of seedbed conditions induced by tillage, and greater weed prevalence, negatively affected spring wheat growth and reduced yield performance under non-inversion tillage treatments compared with CT. This agrees with other studies with similar findings (Arvidsson *et al*., 2013; Brennan *et al*., 2014; Franchini *et al.,* 2012; López-Bellido *et al.,* 1996). Key findings for the 2014 cultivation techniques effects are listed in Table 5.18.

Table 5. 18. Key outcomes for the cultivation techniques effects during 2014 cropping season

	CT	HINiT	LINiT
Tillage intensity	High	Intermediate	Low
Seedbed	Fine	Coarser	Much coarser
Condition	Level/uniform	Variable/Not uniform	Highly variable/Not uniform
Plant establishment	High	High	Low
Tiller production	High	High	Low
Plant height	Statistically not significant		
Ears number	High	Intermediate	Low
TGW	Statistically not significant		
Number of grains per ears	High	Low	Intermediate
Grain yield	High	Low	Low
SMN	High	Low	Low
Moisture content	Statistically not significant		

High rainfall patterns across the cropping season possibly reduced the level of residual SMN, allowing a positive effect of the N fertilisation application on final grain yield, up to 140 kg N ha^{-1}. Under this study weather conditions, it seems that 210 kg N ha^{-1} rate is only required to increase grain protein content. Key outcomes for the N effects are listed in Table 5.19.

Table 5. 19. Key outcomes for the nitrogen fertilisation effects during 2014 cropping season

	N0	N70	N140	N210
Plant height	Low	Medium	High	High
Ears number	Statistically not significant			
TGW	High	Medium	Medium	Low
Number of grains per ears	Low	Low	High	High
Grain yield	Low	Low	High	High
SMN	Highly low	Low	Medium	High

Low precipitation at the time of undersowing caused failure of the undersown legume species as also observed in the 2013 cropping season.

CHAPTER SIX

Effect of weather on spring wheat performance following different cultivation regimes

6.1.Introduction

Shifts in weather patterns and increases in the frequency and magnitude of extreme weather events are a result of the global warming (Lobell *et al*., 2012; Semenov & Shewry, 2011). According to the UK Meterological Office report (Gosling *et al*., 2011), the UK has been warming since 1960 with greater warming in the summer than winter. Gosling *et al.* (2011) report suggests that for the south of the UK an intensification of the frequency of water stress and drought is projected. The increase in air temperature and the incidence of drought associated with global warming are serious threats to crop production (IPCC, 2014a,b; Lobell *et al*., 2013). In the UK, it has been estimated that a potential loss of around 10-20% of typical wheat yield could occur due to drought (Foulkes *et al*., 2001). According to Spink *et al*. (2009), about 12% of the wheat crop in the UK is grown on land susceptible to yield limiting droughts in 2 out of 3 years. In the present study, the 2013 and 2014 cropping seasons experienced contrasting weather conditions, particularly rainfall patterns. The 2013 growing season, experienced higher rainfall conditions at beginning of the growing period in March, and much drier summer months compared with the 2014 season and the long-term seasonal average. The different weather conditions have highlighted the effect of soil management practices adopted reflected in subsequent differences in resultant wheat yields.

The aim of the present study, therefore, is to further investigate weather conditions, in particular rainfall, influences that impact on the effect of cultivation techniques including conventional tillage (CT), high intensity non-inversion tillage (HINiT) and low intensity non-inversion tillage (LINiT), on spring wheat production. Meta-analysis is the statistical combination and summarisation of results from multiples studies (Gurevitch & Hedges, 1999). In the current study a meta-analysis of trial results was conducted to compare and integrate the results of three experimental studies in order to identify general patterns.

6.2. Material and methods

The present study combined and contrasted results from a separate published study with 2013 and 2014 results previously discussed in Chapter 4 and Chapter 5. The published results were obtained from an adjacent organic experimental study (Vijaya Bhaskar *et al.,* 2013b) conducted from March to August 2012 at the Royal Agricultural University's Harnhill' Manor Farm (NGR SP 075 006). The 2012 organic experiment followed a fully factorial treatment structure – *Spring wheat (block) x tillage systems (main plot) x +/- undersowing (subplot)*, with three replicates. All agricultural management treatments used in the organic experiment were present in each following year (2013 and 2014) except for herbicide application and N fertilisation management which were adopted for the 2013 and 2014 periods. For the 2013 and 2014 studies, only the results under an unfertilised N (N0) treatment were used. These studies followed then a fully factorial treatment structure.

Cultivation techniques in 2012 were named differently from the 2013 and 2014 studies. However, in order to maintain a uniform dataset, the terminology for the treatments is as previously used in the 2013 and 2014 studies, as tillage operations were the same. Treatment terminologies adopted in 2012 and their equivalents used in the present study are given in Table 6.1.

Table 6. 1. Cultivation techniques treatments terminology used by Vijaya Bhaskar *et al.* (2013b) and their equivalents in the present study

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The specification details for the cultivation techniques treatments were previously described in Chapter – 3, Material and Methods, § 3.2.2.1. Further details of the spring wheat cropping seasons are given in Table 6.2.

Table 6. 2. Details of the spring wheat cropping seasons

	2012	2013	2014
Cultivation technique treatments	CT, HINiT and LINiT		
Cultivation techniques performance date	09 March	20 March	24 March
Spring wheat	cv Paragon		
Seed rate	420 seed m^2	480 seed m^2	
Sowing date	14 March	10 April	18 April
Harvest date	22 August	27 August	31 August
Average grain yield (t ha^{-1})	2.86	5.79	3.07

Building the database

A database template was designed including the selected data from the 2012 organic study and the 2013 and 2014 data reported in the Chapters 4 and 5. In accordance with the objectives of the present study and the requirements of the meta-analysis, the database was formulated including the following categories: yield, cultivation techniques type, rainfall and standard deviations. The database is given in Appendix 3. The spring wheat growing season was from March to August, therefore, total season rainfall was only considered from those months.

Meta-analysis treatments and calculations

Meta-analysis allows experimental results reported to be combined for analysis towards evaluating overall treatment effects (Gurevitch & Hedges, 1999). To assess the overall effect and to determine the treatments constancy across the studies, mean differences were weighted. Initially, the 2013 and 2014 data were analysed separately, by analysis of variance. Comparisons between the mean of the HINiT treatment and the CT treatment, and their standard errors were calculated from each experiment, and used in a meta-analysis to obtain a consensus estimate combining information from all the experiments (see Whitehead, 2002, Section 4.2.). The same analysis was then done for the comparison between LINiT and CT. Seasonal rainfall was used as a covariant for the crop yield response to cultivation techniques managements. Seasonal rainfall was categorized into low (<300 mm), medium (300-500 mm) and high (>500 mm). The analysis performed produces a plot showing estimates of the comparisons from each

experiment together with the combined estimate, all with 95% confidence regions. The effect is significantly different from zero if its confidence region does not overlap zero. The analyses were performed using the META procedure of Genstat statistical software (15th Edition VSN International Ltd, Hemel Hempstead, UK).

6.3.Results and discussion

Cropping season (March-August) mean air temperatures for the studied years, 2012-2014, were below the 10- year average (2002-2012) temperature (13.9 °C) (Table 6.3). As air temperatures were quite similar between the cropping years studied, for the purpose of this study, only rainfall was evaluate as a covariant for the meta-analysis.

Table 6. 3. Monthly air temperature (°C) for the study period (2012-2014) and for the long-term records (2002-2012). Royal Agricultural University meteorological station, (NGR SP 42 004 011)

	2012	2013	2014	Average	Long term-average (2002 -2012)
March	8.34	3.09	7.18	6.20	7.48
April	6.81	7.31	9.71	7.94	10.28
May	11.84	9.97	12.08	11.30	13.05
June	13.60	13.60	15.25	14.15	16.34
July	15.71	18.94	18.03	17.56	18.27
August	16.55	17.14	14.74	16.15	18.43
Mean	12.14	11.68	12.83	12.22	13.98

Total seasonal rainfall for the 2013 cropping period (292.0 mm) was below the 10-year average seasonal rainfall (377.2 mm) (Table 6.4). Seasonal rainfall in 2012 (589.1 mm) and 2014 (400.5 mm) were above the 10-year average. Categories based on seasonal rainfall were used, instead of experimental year, to label the y-axis in Figure 6.1 and 6.2 below.

Table 6. 4. Monthly and cumulative rainfall (mm) for the study period (2012-2014) and the long-term records (2002-2012). Royal Agricultural University meteorological station, (NGR SP 42 004 011)

	2012	2013	2014	Average	Long term-average (2002 -2012)
March	24.9	76.8	39.5	47.07	51.39
April	126.3	31.5	65.9	74.57	45.37
May	50.9	76.6	97.3	74.93	68.15
June	175	42.5	49.7	89.07	64.60
July	99.8	31.3	56.6	62.57	82.57
August	112.2	33.3	91.5	79.00	65.15
Total	589.1	292.0	400.5	427.2	377.24

The long-term total rainfall for the last 60 years is presented in Figure 6.1. During this period, four extreme events of high rainfall (>1000 mm) occurred, with two events observed in the last 20 years. However, dry years with rainfall <600 mm were more common, recording three out of five in the last 20 years. Figure 6.1 shows the total rainfall divided into cropping season rainfall and off-season rainfall (October-February). From the seasonal rainfall, four events of rainfall >500 mm occurred in the last 60 years, although three out of four were recorded in the last 10 years. In addition, 11 cropping seasons experienced seasonal rainfall <300 mm, with six out of eleven happening in the last 20 years. These results show growing evidence that rainfall patterns are changing with drier and in some cases wetter seasons occurring more frequently.

The amount and distribution of rainfall are crucial for crop performance, including wheat (Mrabet, 2011). Moisture stress at critical growth stages can inhibit root growth, reduce tiller production, diminish wheat vegetative growth and number of grains per ear, and possibly cause poor grain filling (Gooding & Davies, 1997; Mrabet, 2011).

Figure 6. 1. Sixty years of long-term cropping season and off-season rainfall (mm). Royal Agricultural University meteorological station (NGR SP 42 004 011)

★ Seasonal rainfall (solid bars) <300 mm; ⭐ Seasonal rainfall (solid bars) >500 mm.
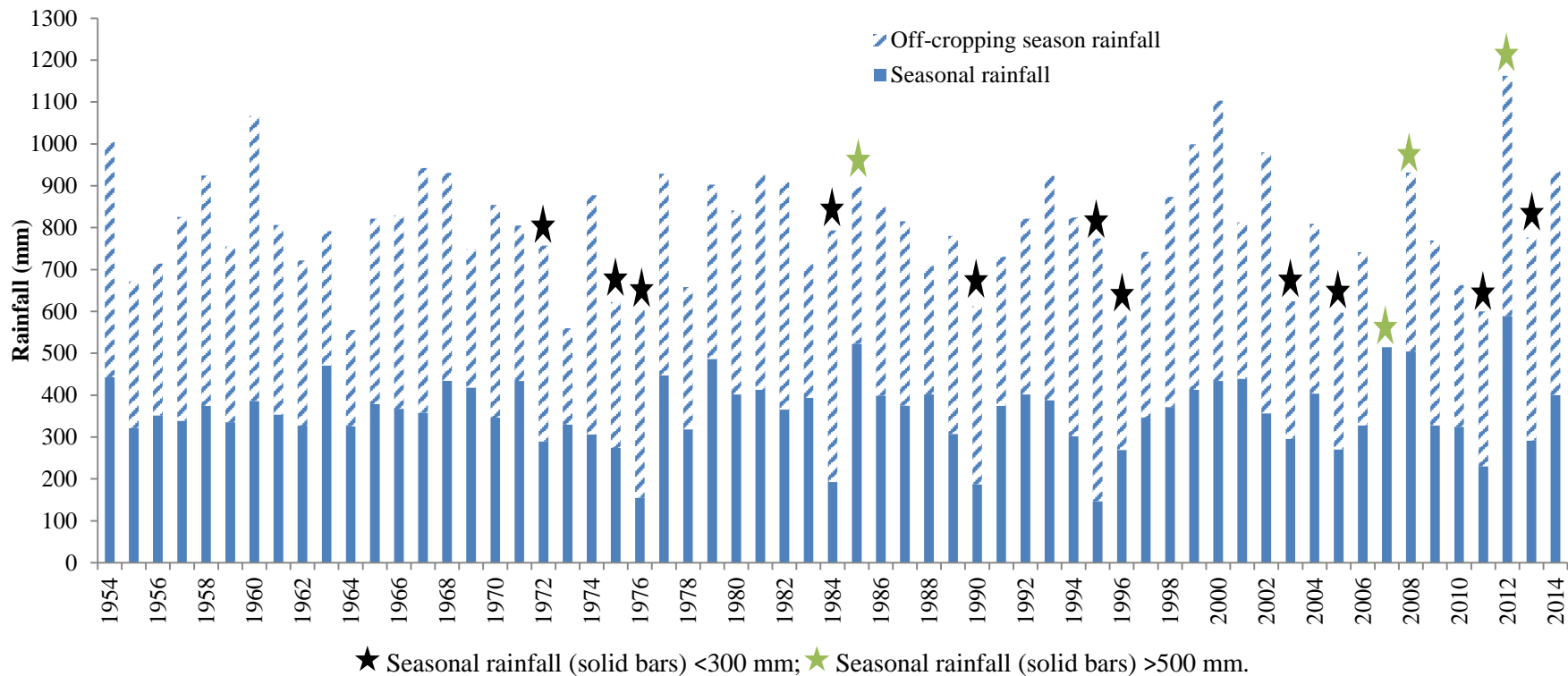
Analysis of the comparison between HINiT and CT showed strong evidence that the effects differ between seasonal rainfall (chi-square 93.6 on 2 df). Figure 6.2 shows that the overall spring wheat yield were 3.23 t ha^{-1} and 0.56 t ha^{-1} higher under CT compared with HINiT, when growing season rainfall were 300 – 500 mm and >500 mm, respectively. There was no evidence of any difference for rainfall <300 mm. Combined over all the studies, yield was higher by 1.34 t ha^{-1} with CT compared with HINiT.

Figure 6. 2. Weighed mean differences in crop grain yield in HINiT compared with CT as affected by growing season rainfall (<300 mm; 300-500 mm; >500 mm)
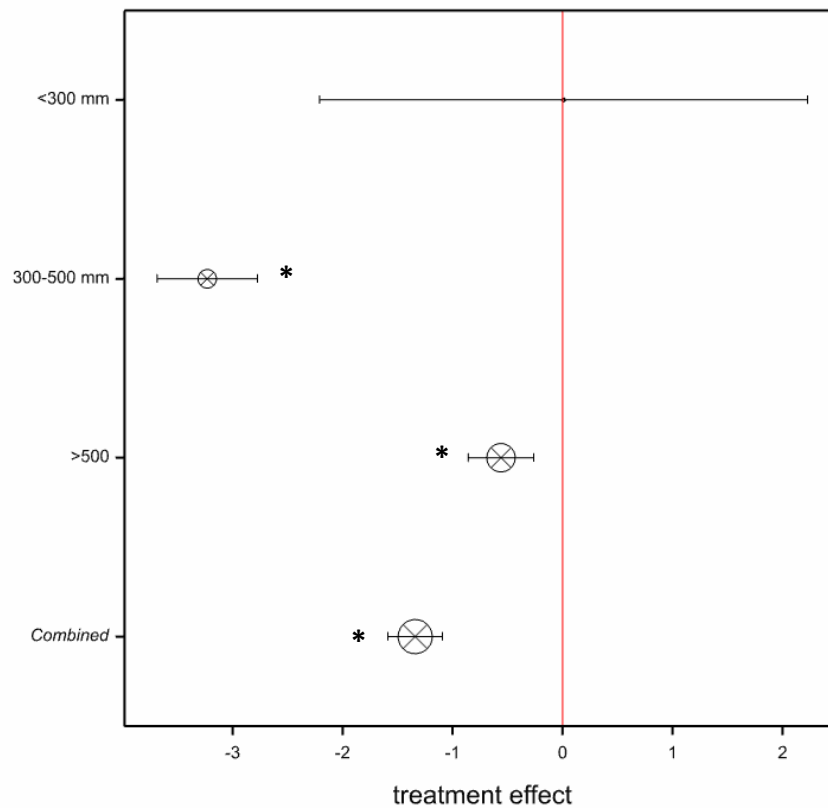
Error bars represent 95% confidence intervals. Significant difference of the effect size is denoted by *.

The analysis of the comparison between LINiT and CT also showed strong evidence that the effect differ between seasonal rainfall (chi-square 33.1 on 2 df). CT resulted in 2.84 t ha^{-1} and 1.41 t ha^{-1} higher grain yield than LINiT when growing season rainfall were 300 – 500 mm and >500 mm (Figure 6.3). There was no evidence of any difference for rainfall <300 mm. Combined over all the studies, yields were higher by 1.80 t ha^{-1} under CT compared with LINiT.

Figure 6. 3. Weighed mean differences in crop grain yield in LINiT compared with CT as affected by growing season rainfall (<300 mm; 300-500 mm; >500 mm)
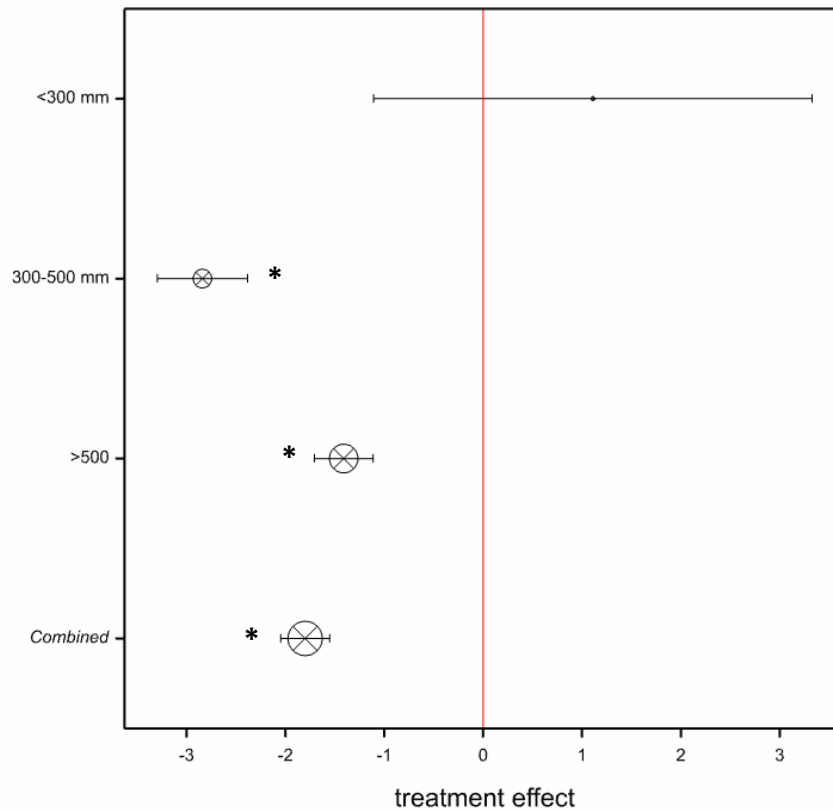
Error bars represent 95% confidence intervals. Significant difference of the effect size is denoted by *.

The significant lower yield under non-inversion tillage under growing season rainfall >300 mm may be attributed to poor infiltration and drainage causing waterlogging problems, as reported by Anazodo *et al.* (1991), Rasmussen (1999) and Rusinamhodzi *et al.* (2011). This may have resulted in wetter and cooler soils under non-inversion tillage (Rasmussen *et al.,* 1993; Reicosky *et al.,* 1995; Riley *et al.,* 2005) reducing plant density and growth, and final grain yields compared with CT. Several authors also report reductions on plant establishment and initial crop growth under non-inversion tillage producing lower yields than CT, under conditions of excessive rainfall (Brennan *et al.,* 2014; Forristal & Murphy, 2009; López-Bellido & López-Bellido, 2001).

The low grain yield under non-inversion tillage in high rainfall conditions could also be related to low soil N availability. Tillage induced effects on soil properties (moisture content, temperature, structure and bulk density) can influence soil N status (Lipiec &

Stepniewski, 1995). Increasing tillage intensity can have several effects including reportedly intensifying soil organic matter decomposition and correspondingly increasing soil mineral N (SMN) content. On the other hand, increasing residue cover and reducing soil disturbance can lead to N immobilisation or slow N release under non-inversion tillage systems. This is supported by several authors (Chen *et al.,* 2007; Franzluebbers, 2004; López-Bellido *et al.,* 2013; McConkey *et al.,* 2002; Soon *et al.,* 2001) reporting higher SMN under CT compared with non-inversion tillage. In conclusion, low N mineralisation potential and high N leaching with high rainfall conditions can lead to low SMN level in soils under non-inversion. This could account for the low grain yield under LINiT and HINiT under high and medium rainfall conditions, compared with CT. Several authors (De Vita *et al*., 2007; Hansen *et al*., 2011; Wang *et al.,* 2012) reported, like in the present study, higher yield under CT with differences on grain yields between tillage systems mainly due to N availability.

The no significant difference between cultivation techniques on final grain yield when the growing seasonal rainfall was <300 mm is perhaps a result of the greater variability of rainfall during the growing season, with occurrence at times of dry periods. Presence of residues on the soil surface under non-inversion tillage could have reduced soil water evaporation, as demonstrated by Freebairn & Wockner (1983) and Stagnari *et al.* (2014). This effect can potentially maintain or increase soil moisture under non-inversion tillage systems reducing stress conditions for the crop, as reported by Cantero-Martínez *et al.* (2003), Kassam *et al*. (2009) and Šíp *et al*. (2013). Positive reduction of soil moisture loss, at time of water need by the crop, can potentially reduce yield differences between tillage treatments in scarcity of rainfall. This, like other studies (Hussain *et al.,* 1999; Lueschen *et al.,* 1991; Piggin *et al.,* 2015; Rusinamhodzi *et al.,* 2011), was particularly evident in the 2013 season when CT and LINiT resulted in similar grain yields, as discussed in Chapter 4.

6.4. Conclusions

Rainfall distribution and amount affected wheat production in the different soil management regimes explored. Meta-analysis of non-inversion tillage compared with

CT showed that grain yields are significantly lower under HINiT and LINiT when total seasonal rainfall is higher than 300 mm. Slow N mineralisation and immobilisation and possible N leaching result in low N availability under reduced tillage practices, while the presence of residues under these tillage systems could generate cool and wet soils negatively affecting crop establishment and growth. These characteristics resulted in the lower grain yield under non-inversion tillage compared with CT under conditions of excessive rainfall. Meta-analysis indicates a similar performance of the non-inversion tillage practices, however, with CT under dry rainfall patterns (<300mm). The potential of the soil under non-inversion tillage to maintain soil moisture can perhaps boost yields making them comparable to those under CT. This is particularly important as results for the 60-years rainfall data shows evidence of increasing frequency of dry seasons at this particular experimental site. In addition, climate change projections for southwest England weather suggest drier summers by up to 40% by 2080s and reduction in summer soil moisture around 30% by the 2050s (Jenkins *et al.*, 2008, 2009).

Integrating data across studies in a meta-analysis can provide an insight of the treatment effects with more precision compared with a single study (Liberati *et al.*, 2009). The present study can, therefore, provide a better understanding of the relative importance of the rainfall patterns and their interaction with crop yield under contrasting tillage practices. However, the number of data sets used is limited and further analysis including larger data set is needed, in order to confirm the present results.

CHAPTER SEVEN

Economic and energy-use evaluation of spring wheat production under different cultivation techniques, nitrogen fertilisation rates and undersowing

7.1. Introduction

In response to increasing global demand for food, energy-use in agriculture has been intensified to maximise yields; minimise labour intensive practices or both (Esengun *et al.,* 2007). The amount of arable land, mechanisation level and labour are amongst the most important factors influencing energy demand in agriculture (Alam *et al*., 2005). The use of combined cultivation machines (for soil disturbance, levelling and seeding) has increased (Morris *et al*., 2010) as the most effective way to save energy and reduce production costs (Hernánz *et al*., 1995). This is possible with reduced tillage operations and work rates potentially decreasing fuel consumption, as reported by Filipovic *et al*. (2006), Hobbs *et al*. (2008) and Koga *et al*. (2003). Non-inversion tillage adoption can potentially reduce the production costs and save operational time compared with conventional tillage (Clement *et al*., 1995; Epplin *et al*., 2005; Morris *et al.,* 2010). Saving time and cost makes the adoption of non-inversion tillage increasingly attractive to farmers, as reported by Harman *et al*. (1996) and Jones *et al*. (2006). However, irregular yield under reduced tillage systems is still reportedly a major concern (Kock *et al.,* 2009; Küstermann *et al.,* 2013; Rochecouste *et al.,* 2015). In contrast, and despite conventional tillage often producing high yields (Arvidsson *et al*., 2013; Brennan *et al*., 2014), it is also the greatest energy and labour consumer in arable crop production (Epplin *et al*., 2005). The use of mineral N fertilisation can often result in higher yields, but it also requires high energy inputs and production costs (Dalgaard *et al.,* 2001; Hussain *et al*., 2010; Refsgaard *et al.,* 1998; Rossner *et al.,* 2014; Sartori *et al*., 2005). More efficient energy-use is one of the considerations towards more sustainable agriculture production. This could provide financial savings, reduction of fossil resources use and less air pollution (Uhlin 1998).

The aim of this study is to investigate energy input and outputs per hectare, and make cost and economic consideration of the adoption of contrasting cultivation techniques, application of N fertilisation and undersowing legumes on spring wheat production.

7.2.Material and methods

7.2.1. Energy considerations

The energy balance was analysed considering only the energy used in crop production, without considering environmental sources of energy (radiation, wind and water). The only energy output considered was the final marketable grain dry weight yield while wheat straw was left on the field and not considered as an economic output. The operations number and duration, seed rate, pesticide and fertiliser application, and human labour data was collected from field measurements and farm records (Royal Agricultural University's Harnhill Manor Farm records). Direct energy (operational energy) includes human energy and fuel consumption, while indirect energy includes machinery, fertiliser, herbicide and seeds. Using a process analysis (Fluck, 1992), total energy consumption was evaluated by summing direct and indirect energies. In the same way, renewable (human labour and seeds) and non-renewables energies (machinery, fuel, fertiliser and herbicides) were investigated. Specifications of the machinery used are included in Appendix 4. The amount of inputs utilised in all core experiments (human labour, machinery, fertilisers, herbicide, seeds and fuel) were specified in Figure 7.1. The amount of input per hectare was multiplied with the coefficient of energy equivalent obtained from the literature (cited in Table 7.1), in order to obtain the energy equivalents for this study. Figure 7.1 also shows the specific energy input by each agricultural management practice used in all core experiments. Energy-use efficiency, energy productivity, specific energy and net energy gain were calculated, as Demircan *et al*. (2006) and Sartori *et al*. (2005),

$$\text{Energy-use efficiency} = \frac{\text{Output energy} \left(\text{MJ ha}^{-1} \right)}{\text{Input energy} \left(\text{MJ ha}^{-1} \right)} \qquad \text{Specific energy} = \frac{\text{Input energy (MJ ha}^{-1})}{\text{Grain yield (kg ha}^{-1})}$$

$$\text{Energy productivity} = \frac{\text{Grain yield (kg ha}^{-1})}{\text{Input energy (MJ ha}^{-1})}$$

$$\text{Net energy gain} = \text{Grain yield} \left(\text{kg ha}^{-1} \right) - \text{Input energy} \left(\text{MJ ha}^{-1} \right)$$

Figure 7. 1. Amount and energy inputs assigned to various agricultural management practices for all core experiments across the cropping seasons

March	April	May	June	July	August

1st fertiliser applic.

Land preparation

Underswowing

Herbicide applic.   Sowing   2nd fertiliser applic.   Harvesting

	Herbicide	CT	HINiT	LINiT	N0	N70	N140	N210	Harvesting
Diesel ($l\ ha^{-1}$)	1.2	38	34	24	0	2.4	2.4	2.4	23
Energy ($MJ\ ha^{-1}$)	67.57	2139.78	1914.54	1351.44	0	135.14	135.14	135.14	1295.13

	Herbicide	CT	HINiT	LINiT	N0	N70	N140	N210	Harvesting
Machinery ($h\ ha^{-1}$)	0.4	1.97	2	1.58	0	0.8	0.8	0.8	1.05
Energy ($MJ\ ha^{-1}$)	25.08	123.52	125.40	99.07	0	50.16	50.16	50.16	65.84

	Herbicide	CT	HINiT	LINiT	N0	N70	N140	N210	Harvesting
Labour ($h\ ha^{-1}$)	0.4	1.97	2	1.58	0	0.8	0.8	0.8	1.05
Energy ($MJ\ ha^{-1}$)	0.78	3.86	3.92	3.10	0	1.568	1.568	1.568	2.06

						BM	WC	Nus
Herbicide ($l\ ha^{-1}$)	2	Wheat seed ($kg\ ha^{-1}$)	200	Fertiliser ($kg\ ha^{-1}$)	0	70	140	210
Energy ($MJ\ ha^{-1}$)	476	Energy ($MJ\ ha^{-1}$)	2940	Energy ($MJ\ ha^{-1}$)	0	16660	33320	49980

	BM	WC	Nus
Seed ($kg\ ha^{-1}$)	8	7	0
Energy ($MJ\ ha^{-1}$)	117.6	102.9	0

Table 7. 1. Energy equivalent of inputs and outputs

Particulars	Unit	Energy equivalent (MJ unit^{-1})	References
Inputs			
Human labour	h ha^{-1}	1.96	Ozkan *et al.* (2004); Yilmaz *et al.* (2005); Singh *et al.* (2002)
Machinery	h ha^{-1}	62.70	Erdal *et al.* (2007); Ozkan *et al.* (2004)
Diesel fuel	l ha^{-1}	56.31	Yilmaz *et al.* (2005); Erdal *et al.* (2007); Singh *et al.* (2002)
N fertilisers	kg ha^{-1}	66.14	Alam *et al.* (2005); Esengun *et al.* (2007) Yilmaz *et al.* (2005); Pervanchon *et al.* (2002)
Herbicide	kg ha^{-1}	238	Ozkan *et al.* (2007)
Seed (wheat)	kg	14.7	Ozkan *et al.* (2004)
Seed (legume)	kg	14.7	Kitani (1999)
Output			
Grain yield	kg	14.7	Ozkan *et al.* (2004); Pimentel (1980)

7.2.2. Economic analysis

Total production cost, expressed as £ ha^{-1}, was calculated by summing inputs cost (fertiliser, herbicide, spring wheat and legume (BM and WC) seeds), and contractor costs for land preparation and drilling (including fuel, labour and transportation of seeds) and combine harvesting (including carting and filling stage). Contractor costs were obtained from the Royal Agricultural University's Farm records. Fixed costs as labour, machinery power and overheads are included in the contractor costs, therefore, no fixed costs are detailed in the present study. Spring wheat grain price was based on the price quoted from the 2013 Farm Management Pocketbook (Nix, 2012) and adjusted by protein content, using grain yield and protein content raw data from each core experiment. Table 7.2 listed costs considered for all core experiments. Total production value, gross return, net return and benefit:cost ratio were calculated following Canakci *et al.* (2005) and Zangeneh *et al.* (2010).

Total production value = wheat yield (t ha^{-1}) x wheat price (£ t^{-1})

Gross return = Total production value (£ ha^{-1}) – Total variable cost (£ ha^{-1})

$$\text{Benefit:cost ratio} = \frac{\text{Total production value } \left(\text{\pounds ha}^{-1}\right)}{\text{Total production cost } \left(\text{\pounds ha}^{-1}\right)}$$

Table 7. 2. Seeds cost, contractor costs and grain price considered for all core experiments

Parameter		Cost	Source
Spring wheat	197 kg ha^{-1} @ £400 t^{-1}	£78.8 ha^{-1}	Nix (2012)
White clover	7 kg ha^{-1} @ £9.30	£65.1 ha^{-1}	Cotswolds Seeds Ltd.
Black medic	8 kg ha^{-1} @ £12.00	£96.0 ha^{-1}	Cotswolds Seeds Ltd.
CT	Kverneland reversible plough + Power harrow combination seed drill	£50 ha^{-1} & £45 ha^{-1}	Royal Agricultural University's Farm records
HINiT	2 passes of ST bar attached Simba X-press + Vaderstadt seed drill	£62 ha^{-1} & 31 ha^{-1}	Royal Agricultural University's Farm records
LINiT	1 pass of ST bar attached Simba X-press + Eco-dyn integrated seed drill	£31 ha^{-1} & £34 ha^{-1}	Royal Agricultural University's Farm records
Fertiliser sprayer	CASE IH SP3000	£12 ha^{-1}	Royal Agricultural University's Farm records
N70	70 kg N ha^{-1} @ £0.74 kg N (£255 t^{-1} fertiliser)	£51.8 ha^{-1}	Royal Agricultural University's Farm records
N140	140 kg N ha^{-1} @ £0.74 kg N (£255 t^{-1} fertiliser)	£103.6 ha^{-1}	Royal Agricultural University's Farm records
N210	210 kg N ha^{-1} @ £0.74 kg N (£255 t^{-1} fertiliser)	£155.4 ha^{-1}	Royal Agricultural University's Farm records
Herbicide sprayer	CASE IH SP3000	£12 ha^{-1}	Royal Agricultural University's Farm records
Glyphosate (Roundup) herbicide	2 l ha^{-1} @ £6.3 l^{-1}	£12.6 ha^{-1}	Royal Agricultural University's Farm records
Combine harvesting		£80 ha^{-1}	Royal Agricultural University's Farm records
Grain price	grain protein < 13%	£150 t^{-1}	Nix (2012)
Grain price	grain protein > 13%	£164.4 t^{-1}	Nix (2012)

Microsoft Excel – 2010 was used to perform general calculations. Energy budget and economic balance were analysed following a split-split plot analysis of variance (ANOVA) model in Genstat (15th Edition VSN International Ltd, Hemel Hempstead, UK). Results are reported as described in Chapter 3, Material and Methods, §3.5.

7.3. Results and discussion

7.3.1. Energy considerations

Input energy in agriculture can be classified as either direct or indirect (Mohtasebi *et al*., 2008). Direct energy is the energy used directly by the operations, which are mainly human labour and fuel, while indirect energy include fertiliser, herbicide and crop seed inputs. The total energy inputs, including direct, indirect, and renewable and non-renewable energy inputs are summarised in Figure 7.3. Increasing tillage intensity increased the amount of direct and indirect energy used, hence total input energy, as also suggested by Knight (2004). This is due to higher work rate, machinery energy and mainly by higher fuel consumption under CT, compared with HINiT, and by LINiT (Figure 7.2). Non-renewable energy required by CT was higher, therefore, compared with non-inversion tillage. In contrast, renewable energy was relatively similar between tillage systems. Alhajj-Ali *et al.* (2013) also reported higher fuel consumption under CT compared with reduced tillage systems. Reducing tillage intensity and the use of a multi-tooled cultivation approach, therefore, can save field operations - including labour, diesel fuel and machinery energy. Several authors (Khaledian *et al*., 2014; Rathke *et al.,* 2007; Ziaei *et al*., 2015) agree that CT operations require higher energy compared with reduce tillage practices, although values differ due to soil type, field conditions and working depths.

Overall, the main source of energy input for spring wheat production was N mineral fertiliser (Figure 7.2). This agrees with several studies (Camargo *et al.,* 2013; Deike *et al.*, 2008; Piringer & Steinber, 2006; Safa *et al.*, 2011) reporting mineral fertilisation as the most important source of energy in conventional wheat production. Alhajj-Ali *et al.* (2013) also reported a linear relationship between increasing energy input and increasing N fertiliser rate. However, under unfertilised conditions diesel fuel was the

main energy source (Figure 7.2), as also reported under organic systems (Vijaya Bhaskar, 2014).

Figure 7. 2. Energy consumption for all core experiments (MJ ha^{-1})
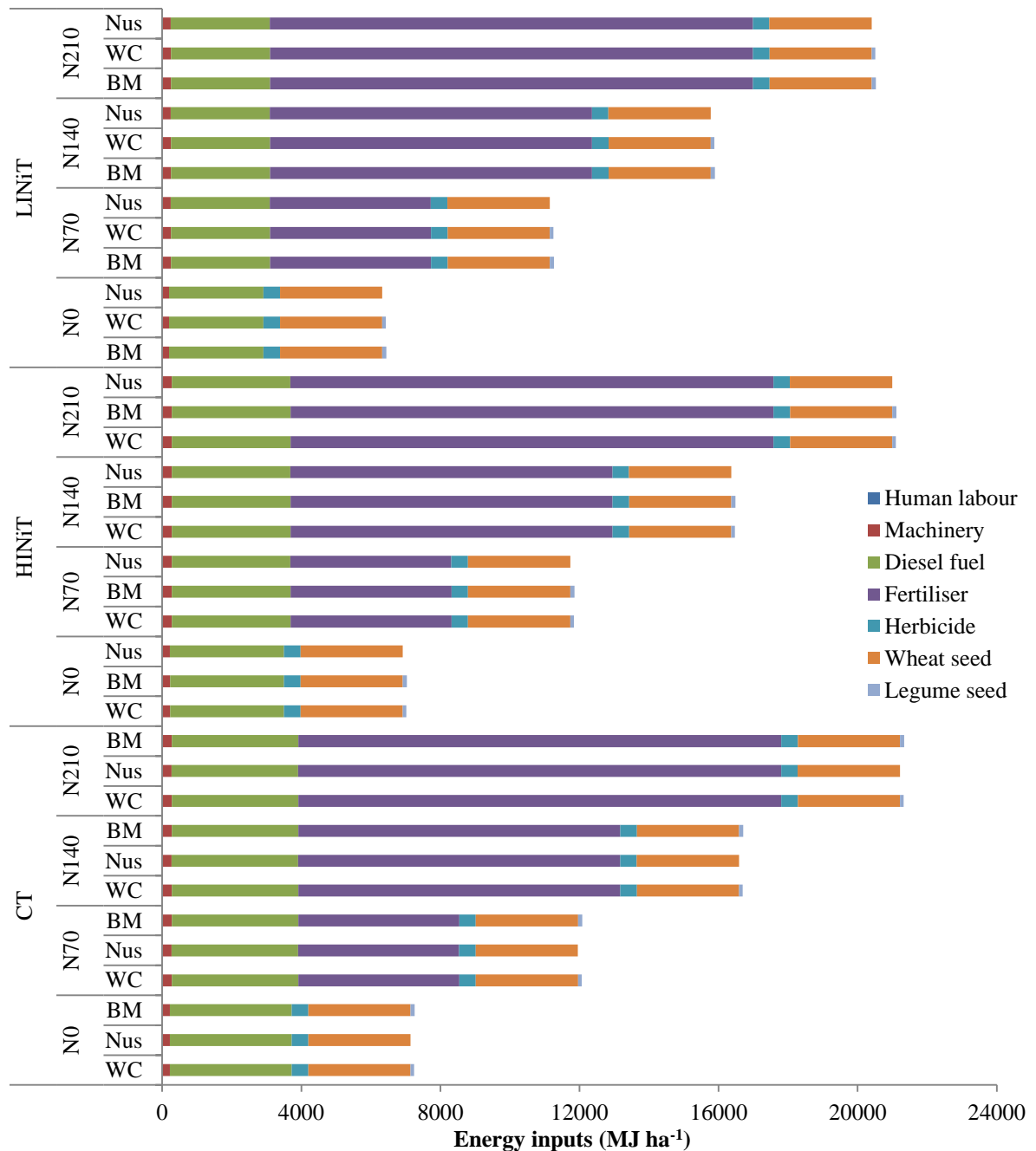
Figure 7. 3. Direct and indirect input energy, and renewable and non-renewable energy for all core experiments

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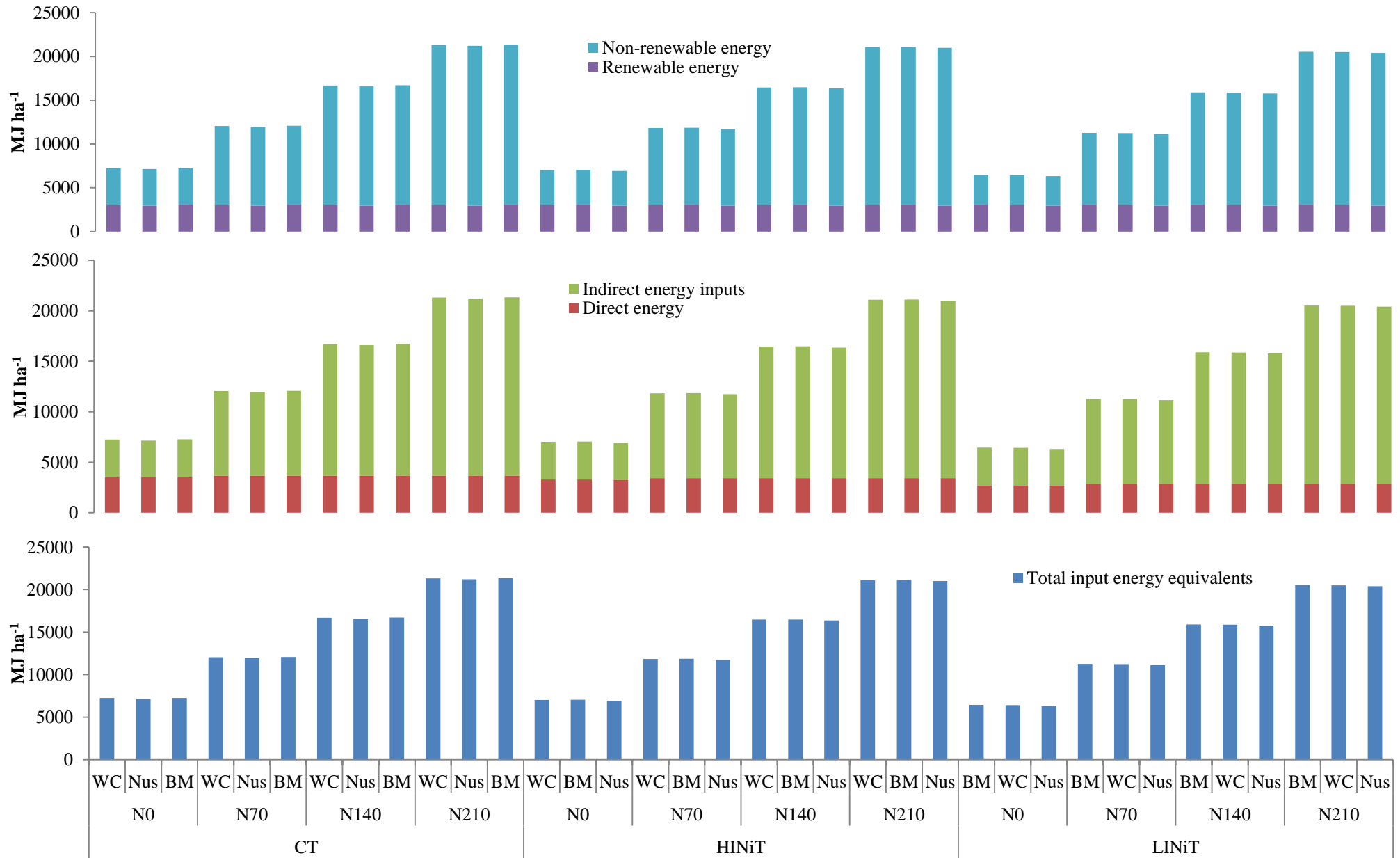
Manufacturing one weight unit of herbicide active ingredient is energy intensive on principle (Green, 1987). However, in the present study, due to the low rate per hectare of herbicide application used, its contribution to the total energy consumption was small, as also reported by Clement *et al.* (1995). Nevertheless, unlike organic farming (e.g. Vijaya Bhaskar, 2014), the herbicide application added 476 MJ ha^{-1} of the energy input increasing total energy consumption across all core experiments (Figure 7.2).

In 2013, LINiT had significantly higher output energy and energy gain than HINiT, and was statistically similar to CT (Table 7.3). Similarly, LINiT resulted in significantly higher energy-use efficiency and energy productivity than CT and HINiT. This suggests that in the case of LINiT, 0.546 kg of wheat yield was obtained per unit of energy used (MJ) (energy productivity). Hernánz *et al.* (1995) also reported greater energy productivity when reducing tillage intensity, compared with CT. The specific energy was significantly lower under LINiT than HINiT and statistically similar to CT. Differences among tillage systems resulted as LINiT produced significantly more yield with less total inputs than HINiT, whereas LINiT yielded statistically similar than CT but using less total inputs. This agrees with Zentner *et al.* (2004) reporting that energy efficiency and energy productivity can be increased either by increasing total energy output or by decreasing total energy input, and by both actions at the same time. In contrast, Borin *et al.* (1997) reported that decreasing tillage intensity increases energy efficiency due to lower output energy used.

Table 7. 3. Analysis of energy indices for spring wheat production in 2013

	Yield (kg ha^{-1})	Output energy (MJ ha^{-1})	Energy-use efficiency (MJ ha^{-1})	Energy productivity (kg MJ^{-1})	Specific energy (MJ kg^{-1})	Net gain (MJ ha^{-1})
CT	5576ab	81968ab	6.690a	0.4551a	2.659ab	68054ab
HINiT	5299a	77902a	6.605a	0.4493a	2.843b	63830a
LINiT	6075b	89309b	8.019b	0.5455b	2.413a	75822b
SED (4df)	*206.8**	*3040.0**	*0.6953***	*0.01704***	*0.0934**	*2846.2***
N0	5610a	82473a	12.077c	0.8215c	1.312a	75609a
N70	5498a	80815a	6.934b	0.4717b	2.267b	69129a
N140	5858a	86118a	5.285a	0.3595a	2.921b	69802a
N210	5635a	82833a	4.123a	0.2805a	4.054c	62401a
SED (18df)	*435.2^{ns}*	*6397.9^{ns}*	*1.5434****	*0.04997****	*0.3397****	*6544.2^{ns}*

Values followed by same letter, do not differ significantly at *P<0.05*. *= *P<0.05*, **= *P<0.01*; ***= *P<0.001*; and ns= no significant

In 2013, N fertilisation did not significantly affected final grain yield, and thus output energy. However, energy-use efficiency and energy productivity decreased with increasing N fertilisation rates. Unfertilised conditions resulted in 0.822 kg MJ^{-1} of energy productivity compared to 0.281 kg MJ^{-1} when 210 kg N ha^{-1} was applied. This suggests that less total energy input under unfertilised conditions increased energy productivity. Accordingly, the specific energy increased with increasing N rate. Net gain was not, however, significantly affected by N fertilisation. These energy indices resulted as increasing N increased total inputs while, total outputs were similar between N rates, as also reported by Alhajj-Ali *et al.* (2013). In contrast to the 2013 results, Safa *et al.* (2011) reported that the consumption of indirect energy by N application is positively correlated with wheat yield.

Introducing a legume crop into the cropping systems can potentially reduce the demand for mineral fertiliser by the main crop (Lupwayi *et al.,* 2011; Schwenke *et al.,* 2011). The present study, however, revealed that undersown legume did not provide significant advantage to the cereal crop and resulted in similar energy-use efficiency than the no undersown treatment (Table 7.3). Nevertheless, undersown legumes significantly interacted with N fertilisation rates affecting energy-use (Figure 7.4 & 7.5). The additional energy inputs by BM and WC seeds combined to the extra energy added with high N rates resulted in lower energy-use efficiency and productivity under those treatments.

Figure 7. 4. Nitrogen fertilisation and undersowing treatment interaction effect on energy-use efficiency (2013)

Error bars representing LSD (*P*<0.05)
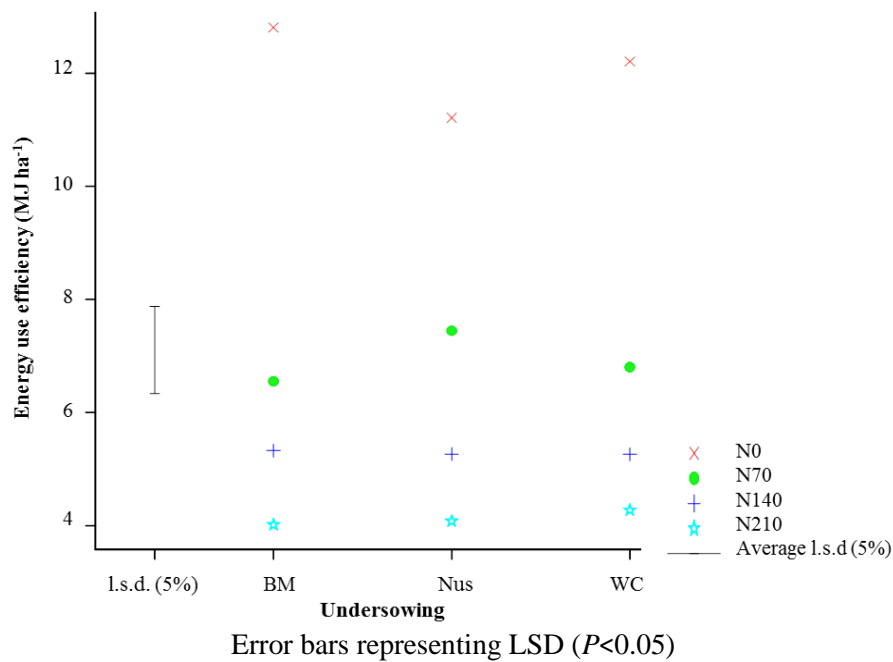
Figure 7. 5. Nitrogen fertilisation and undersowing treatment interaction effect on energy productivity (2013)

Error bars representing LSD (*P*<0.05)
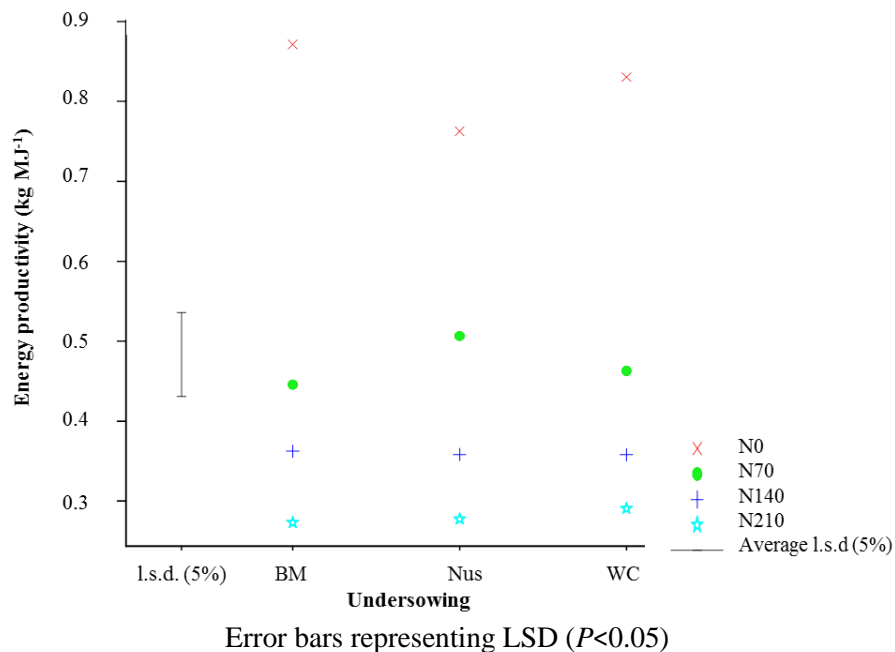
In the 2014 season, CT resulted in a significantly higher yield, thus higher output energy than non-inversion tillage systems (Table 7.4). Energy-use efficiency, energy

productivity and net gain were higher under CT followed by LINiT, and HINiT. Despite the fact that direct and indirect input energies were lower under HINiT, output energy was significantly lower than CT, reducing its efficiency. This agrees with Borin *et al.* (1997) reporting that decreasing tillage intensity reduces output energy resulting in lower energy efficiency. Non-inversion tillage systems had less fuel consumption, machinery energy and have a higher work rate. Coarser seedbed conditions resulted in poorer plant establishment and plant growth, however, and greater weed competition (see Chapter 5) affecting the energy-use efficiency. This agrees with Küsterman *et al.* (2013) reporting that the benefit of reduced tillage systems over CT is mainly due to lower input energy as outputs are often lower.

Table 7. 4. Analysis of energy indices for spring wheat production in 2014

	Yield (kg ha^{-1})	Output energy (MJ ha^{-1})	Energy-use efficiency (MJ ha^{-1})	Energy productivity (kg MJ^{-1})	Specific energy (MJ kg^{-1})	Net gain (MJ ha^{-1})
CT	5371b	78951b	6.465c	0.4398c	2.60a	65037c
HINiT	2533a	37228a	2.883a	0.1962a	6.62a	23152a
LINiT	3196a	46981a	3.764b	0.2561b	4.43a	33492b
SED (4df)	*265.8****	*3907.0****	*0.246****	*0.01672****	*1.193^{ns}*	*3700.5****
N0	3097a	45524a	6.548c	0.4455c	2.766a	38652a
N70	3264a	47983a	4.079b	0.2775b	4.413ab	36297a
N140	4182b	61478b	3.759b	0.2557b	4.709ab	45162a
N210	4256b	62562b	3.097a	0.2107a	6.316b	42131a
SED (18df)	*290.1****	*4264.6****	*0.310****	*0.0211****	*0.953***	*4241.3^{ns}*

Values followed by same letter, do not differ significantly at *P<0.05*. **= *P<0.01*; ***= *P<0.001*; and ns= no significant

The application of 140 and 210 kg N ha^{-1} in the 2014 season resulted in significantly higher output energy in terms of grain yield, compared with unfertilised condition and low N rate (70 kg N ha^{-1}) (Table 7.4). However, increasing N rates increases total energy inputs as both direct and indirect energy inputs increases. This decreases the energy-use efficiency and energy productivity when raising N rates, although no significant differences were observed between N70 and N140. Sartori *et al.* (2005) also reported that reducing chemical inputs potentially increases energy-use efficiency. The specific energy was significantly higher when 210 kg N ha^{-1} was applied compared

specifically with unfertilised conditions, as output energy increased with increasing total energy inputs.

In 2014 CT treatment combined with N fertilisation had a significantly lower energy-use efficiency and energy productivity, particularly when compared with unfertilised conditions (Figure 7.6 & 7.7). This resulted from those treatment combinations that produced high output energies but also required high direct and indirect energy inputs.

Figure 7. 6. Cultivation techniques and nitrogen fertilisation treatment interaction effect on energy productivity (2014)

Error bars representing LSD (*P*<0.05)
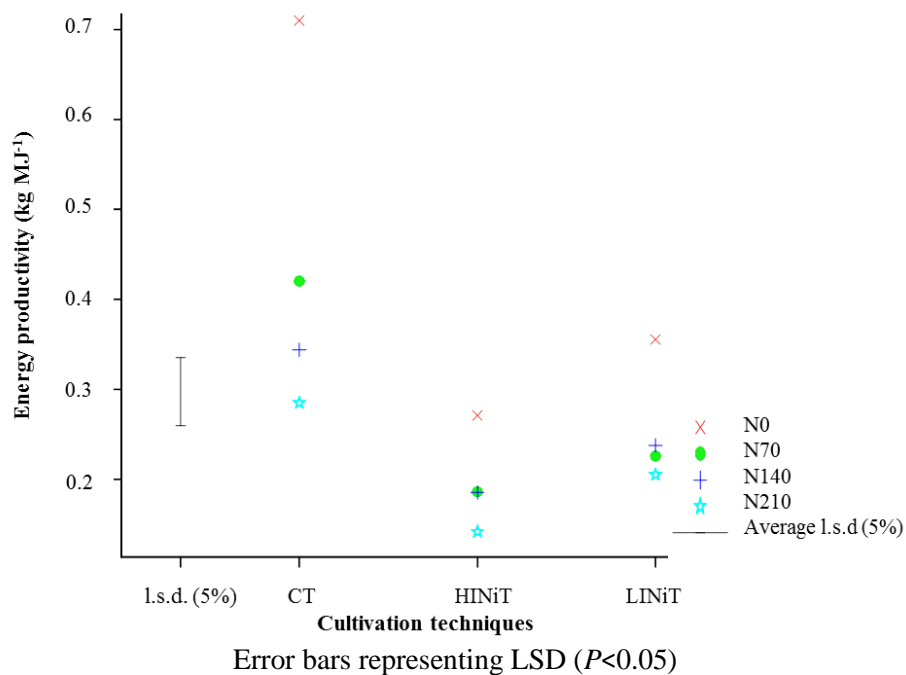
Figure 7. 7. Cultivation techniques and nitrogen fertilisation treatment interaction effect on energy-use efficiency (2014)

Error bars representing LSD (*P*<0.05)
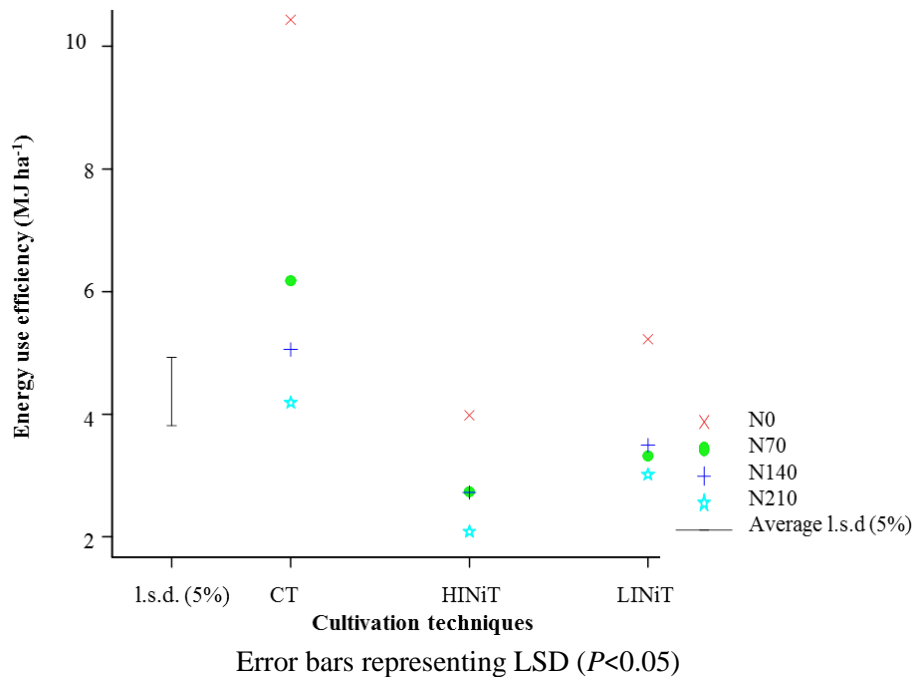
7.3.2. Economic analysis

Irrespective of the year studied, no fixed costs were evaluated as machinery power and labour were included in the contractor cost for land preparation and drilling, and fertiliser and herbicide spraying operations. Total production cost, therefore, coincides with total variable cost. Overall, in the present study, production costs were higher comparing with organic farming (e.g. Vijaya Bhaskar, 2014) where mineral fertilisation and herbicide application would be proscribed.

Across experiments, total production cost was lower under LINiT, compared with HINiT, and by CT (Table 7.5 & 7.6), agreeing with Hernánz *et al*. (1995) and Knight (2004). Increasing N fertilisation rates increases production cost, while BM resulted in higher total production cost compared with WC, and compared with the no undersowing conditions, as BM seed price is higher.

In the 2013 spring wheat season, LINiT had a significantly higher gross return, compared with HINiT and CT (Table 7.5). Production value per unit of production cost (benefit:cost ratio) was also significantly higher with LINiT (2.59), than CT (2.15) and

HINiT (2.04). The lower contract cost for land preparation and drilling, and greater yield produced resulted in higher gross margin and also the benefit:cost ratio under LINiT, compared with HINiT and CT. Despite the statistically similar grain yields between CT and LINiT, high production cost under CT resulted in a lower gross margin and benefit:cost ratio. In the same context, low production cost under HINiT has not rewarded with a greater gross return.

Table 7. 5. Economic analysis for spring wheat production in 2013

	Yield (t ha^{-1})	Total production value (£ ha^{-1})	Total production cost (£ ha^{-1})	Gross return (£ ha^{-1})	Benefit:cost ratio
CT	5.58ab	863.4	409.8	453.6a	2.15a
HINiT	5.29a	814.6	407.8	406.7a	2.04a
LINiT	6.08b	950.7	379.8	570.9b	2.59b
SED (4 df)	*0.207**	-	-	*33.4**	*0.09***
N0	5.61a	846.6	321.43	525.1a	2.64b
N70	5.50a	834.5	373.23	461.3a	2.29a
N140	5.86a	904.0	425.03	478.9a	2.16a
N210	5.63a	919.8	476.83	442.9a	1.95a
SED (18 df)	*0.435^{ns}*	-	-	*67.2^{ns}*	*0.17***
BM	5.65a	882.7	441.43	441.3a	2.04a
Nus	5.60a	867.0	345.43	521.6a	2.56b
WC	5.70a	878.9	410.53	468.4a	2.17a
SED (48 df)	*0.215^{ns}*	-	-	*33.8^{ns}*	*0.08****

Values followed by same letter, do not differ significantly at $P<0.05$. *= $P<0.05$, **= $P<0.01$; ***= $P<0.001$; and ns= no significant

Between N rate treatments in 2013 the unfertilised conditions resulted in a significantly higher benefit:cost compared with any other N rate application. The N fertiliser increased production costs compared with unfertilised conditions. This, in addition to N fertilisation failing to increase 2013 grain yield (Chapter 4), resulted in a significantly lower benefit:cost ratio, compared with the unfertilised conditions (Table 7.5).

Higher production costs when using undersown legume species resulted in significantly lower benefit:cost than no undersowing, as the legume did not offer any advantage to grain yields in the drier weather conditions.

In 2014 the gross return was highly dependent on grain yield value, which was significantly higher under CT than non-inversion tillage treatments (Table 7.6). Despite high production costs relating to CT, increases in yield output resulted in a significantly high gross margin. Although production costs were quite similar between CT and HINiT, the more variable seedbed conditions and greater weed pressure under HINiT negatively affected yield. This reduced production value resulting in a negative gross margin under HINiT. Higher production value and lower production cost under LINiT resulted in a significantly higher benefit:cost ratio (1.28) than HINiT (0.95).

Table 7. 6. Economic analysis for spring wheat production in 2014

	Yield (t ha^{-1})	Total production value (£ ha^{-1})	Total production cost (£ ha^{-1})	Gross return (£ ha^{-1})	Benefit:cost ratio
CT	5.37b	844.7	409.8	434.9c	2.11c
HINiT	2.53a	388.2	407.8	-19.6a	0.95a
LINiT	3.20a	491.2	379.8	111.4b	1.28b
SED	*0.266***	-	-	*44.2***	*0.114****
N0	3.10a	468.6	321.43	147.1a	1.48a
N70	3.26a	493.0	373.23	119.7a	1.32a
N140	4.18b	655.5	425.03	230.5a	1.56a
N210	4.25b	681.8	476.83	204.9a	1.44a
SED	*0.290***	-	-	*45.3^{ns}*	*0.109^{ns}*
BM	3.75a	581.8	441.43	140.3a	1.31a
Nus	3.72a	580.8	345.43	235.4b	1.68b
WC	3.63a	561.5	410.53	151.0a	1.36a
SED	*0.207^{ns}*	-	-	*33.1***	*0.089****

Values followed by same letter, do not differ significantly at *P<0.05*. **= *P<0.01*; ***=*P<0.001*; and ns= no significant

N fertilisation, in the 2014 season, significantly increased production value but also total production costs, resulting in non-significant differences on the gross return and benefit:cost ratio between N rates (Table 7.6). This is more evident with the application of 210 kg N ha^{-1} resulting in statistically higher protein content, compared with any other N rate (see Chapter 5). However, this N rate also increased production costs, resulting in no significant differences on the benefit:cost.

Increases in production costs by including undersown legumes resulted in a lower gross margin and benefit:cost ratio (Table 7.6).

7.4. Conclusion

The present study aimed to identify agricultural management operations where energy and cost savings could be realised. It appears that the energy and economic performances of the different agricultural management practices used in this case were dependent on specific characteristic affecting the final crop yield and grain protein content – such as weather conditions, agreeing with Gomiero *et al.* (2011).

It seems that regardless of high input energy and production costs, CT can potentially be efficient in the energy-use and economically viable. However, in considering low energy consumption and production costs, this study showed that LINiT is the most reliable alternative to CT systems. LINiT exhibited promising results in increasing productivity and economic returns when a resultant high crop yield is delivered.

The application of mineral N is energy consuming and costly. Results of the present study showed that N fertilisation is not always energy-efficient and economically viable, even when it can result in higher final yields. However, the yield and grain quality responses and grain value remain key, with higher crop performance providing greater justification.

For all experiments, undersowing BM and WC was economically less profitable than no undersowing. However, in terms of energy consumption, no differences between undersowing were found for either BM or WC.

In order to assess sustainability of the agricultural management practices used in the present study over the long-term, further investigation of wider economic and energy impacts (such as soil carbon sequestration and greenhouse gas emissions) could be addressed, together with consideration of the wheat straw output inclusion.

CHAPTER EIGHT

General discussion and conclusions

8.1.Introduction

The primary objective of the present study was to investigate the effects of selected cultivation techniques, N fertilisation and undersown legumes on spring wheat growth and development. To explore, in particular, the yield components that contribute to grain yield and quality, as well as weed pressure influences alongside changes in soil mineral N content. This was examined through field experiments on a clay soil using three cultivation techniques - from conventional tillage through high intensity non-inversion tillage to low intensity non-inversion tillage; four mineral N fertilisation rates of 0, 70, 140 and 210 kg N ha^{-1} and two undersown legume species - black medic and white clover plus no undersowing treatment. Figure 8.1. shows links between all the thesis chapters, and how each study contributes and attempts to assess the most suitable agricultural management practices for increasing yield, and yet be the most efficient in energy-use and profitability.

Chapter 1 and 2 set the framework of the agricultural management practices adopted, and the effects on crop performance and weed prevalence reported in previous studies (Literature review). The methodologies and techniques utilised to establish and evaluate the two experimental trials are developed and described in Chapter 3. Data sets were collected across the two core experiments established in 2013 and 2014. As analysis combining core experiments over time did not show any progress compared to single data sets - core experiments were then analysed separately and presented in Chapter 4 and 5 (Core experiment 1 & 2). Based on results obtained from both core experiments, the effect of the weather conditions on spring wheat performance under contrasting cultivation regimes was evaluated by performing a meta-analysis (Chapter 6). Finally, Chapter 7 focuses on the energy-use and economic productivity of the management practices adopted. Chapter 8 deals with how the whole study is able to provide an improved understanding of the influences of the agricultural practices on crop development, soil mineral N content and weed infestation. This chapter also reaches key conclusions, and considers some implications and suggestions for further work.

Figure 8. 1. Chapters interlinking different agricultural management practices, weather conditions, and energy and economic considerations for spring wheat production

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┌─────────────────────────────────────────────────────────────┐
│      Problem statement and research objectives (Chapter 1)     │
│                                                                 │
│  Review of challenges related to cultivation techniques,       │
│  mineral N fertilisation and undersowing legumes effects on    │
│  spring wheat production (Chapter 2)                           │
└─────────────────────────────────────────────────────────────┘
                              │
                              ▼
              ┌──────────────────────────────────┐
              │  Core experimental studies in      │
              │  2013 and 2014                     │
              │  (Chapters 3, 4 & 5)               │
              └──────────────────────────────────┘
                   │                        │
                   ▼                        ▼
  ┌──────────────────────────┐   ┌──────────────────────────┐
  │  Meta-analysis of spring  │   │  Energy and economic      │
  │  wheat performance under  │   │  evaluation               │
  │  different cultivation    │   │  (Chapter 7)              │
  │  techniques regimes       │   │                           │
  │  (Chapter 6)              │   │                           │
  └──────────────────────────┘   └──────────────────────────┘
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8.2. Cultivation techniques

8.2.1. Wheat performance

Key findings for the contrasting cultivation treatments adopted are summarised in Table 8.1. The use of the plough and power harrow under conventional tillage (CT) created a fine and uniform seedbed favouring plant germination and establishment in all of the seasons studied. This is mainly the result of the plough inverting the soil and incorporating plant residues. The power harrow breaks massive structure of clay soil leaving a fine and level seedbed, assumingly increasing soil-seed contact as previously reported (Atkinson *et al*., 2007, 2009; Bell, 1996; Comia *et al.,* 1994). Seedbed conditions created by non-inversion tillage systems, such as high intensity non-inversion tillage (HINiT) and low intensity non-inversion tillage (LINiT) reduced crop emergence and final establishment when compared with CT, as also reported by Känkänen *et al.* (2011) and Pietola & Tanni (2003). This is likely to be due to large amount of plant residues on the soil surface and the increased presence of soil clods, leaving a much coarser and variable seedbed, as others have widely reported (Atkinson, 2008; Morris *et al*., 2010; Känkänen *et al.,* 2011; Rieger *et al*., 2008). HINiT and LINiT systems can also keep the soil surface wet and cold by reducing soil evaporation which negatively affects crop emergence and early growth, as Morris *et al.* (2010) and Reicosky *et al.* (1995) reported.

Table 8. 1. Key findings for contrasting cultivation techniques for all core experiments

	CT	HINiT	LINiT
Tillage intensity	High	Intermediate	Low
Seedbed	Fine	Coarser	Highly coarser
Seedbed evenness	Level / Uniform	Variable / Not uniform	Highly variable / Not uniform
Plant establishment	High	[2]High / [1]Intermediate	Low
Tiller production	High	High	Low
Plant height	Statistically not significant		
Ears number	High	[1]High / [2]Intermediate	Low
TGW	Statistically not significant		
Number of grains per ear	[2]High / [1]Low	Low	[1]High / [2]Intermediate
Grain yield	[*]Comparable / [2]High	Low	[1]High / [2]Low
SMN	[2]High / [1]Low	[1]Intermediate / [2]Low	[1]High / [2]Low
Moisture content	[1]Low	[1]Intermediate	[1]High

[1]Only observed in 2013 season (Chapter 4); [2]Only observed in 2014 season (Chapter 5); [*]Statistically comparable with LINiT and HINiT

One of the core objectives of the present study focussed on spring wheat performance and productivity. In all experiments, the performance of different cultivation techniques on spring wheat production was the result of complex interactions between seedbed conditions, moisture status, N availability, weed pressure and variable rainfall conditions (Table 8.1). This emphasises the difficulties of relating final grain yield to a particular yield limiting factor, as highlighted by Gooding & Davies (1997).

Contrary to the finding of several authors (e.g. Blake *et al*., 2003; Ghaderi *et al*., 2009), the present study did not always observe positive relationships between crop establishment and final grain yield. Weather conditions, especially rainfall, also exerted considerable influences on grain yield. The contrasting performance of the cultivation techniques treatments on wheat production in each core experiment have been attributed to various causes (Chapter 4, 5 & 6). The present study showed that under conditions of low rainfall, maintaining or increasing soil moisture can considerably positively influence final grain yield (Core experiment I). In the 2013 cropping season the ability to conserve soil moisture and the high resultant SMN content appear to compensate for

poor establishment and the initial slow crop growth under LINiT, finally making crop yield comparable to CT. This is particularly important as drought events in the UK are expected to increase (DEFRA, 2012; Spink *et al*., 2009), and LINiT may, therefore, potentially reduce crop stress conditions. As in this study, several have reported the benefit of non-inversion tillage under low rainfall conditions (De Vita *et al.,* 2007; López-Bellido *et al.,* 2000; Martinez *et al.,* 2008; Stagnari *et al.,* 2014). Nevertheless, when water availability is not a limiting factor (as in Core experiment II), poor plant establishment, high variability of crop growth, low SMN content and high weed pressure under the non-inversion tillage adversely affected crop performance and resulted in lower crop yield compared with CT. These findings agree with other studies (Arvidsson *et al*., 2013; Brennan *et al*., 2014; Franchini *et al.,* 2012; McConkey *et al*., 2002; Vijaya Bhaskar et al., 2013b). The initial advantages of CT of better plant establishment and crop growth, mostly led to higher final grain yield than non-inversion tillage systems (Core experiment II).

Taking into account such factors as seedbed variability and complexity, and also weed pressure, the present study considers that conventional tillage (CT) has the greatest potential for ensuring a more reliable spring wheat yield performance in a given soil and location. However, considering climate uncertainty with dry seasons, Low Intensity Non-inversion Tillage (LINiT) also shows promising potential to be an optional practice to CT, in providing better soil moisture conditions in dry weather.

8.2.2. Weed pressure

The influences of cultivation techniques on weed growth have been documented by several authors (Froud-Williams *et al*., 1981; Hakansson, 2003; Menalled *et al*., 2001). Across the current core experiments, increasing weed pressure was generally observed under non-inversion tillage systems, although this was variable. Table 8.2. summarises the cultivation effects on weed pressure across core experiments. Overwinter assessment in 2013 showed that LINiT potentially allow weeds to grow, as more weed seeds stay in the soil surface after harvest practices, supporting the finding of other studies (Ball, 1992; Tuesca & Puricelli, 2007).

Table 8. 2. Trends in weed growth between cultivation techniques across core experiments

	CT	HINiT	LINiT
2013 overwinter weeds	Low	Low	High
Early total weed	[1]Low	[1]High	[1]Low
Mid-season total weed	Low	High	[1#]Comparable / [2]High
Broadleaf weed species	Low	High	[1]Low / [2]Intermediate
Grass weed species	Statistically not significant		
Weed prevalence (from early growth assessments to harvest)	[2]Low	[2]High	[2]High

[1]Only observed in 2013 season (Chapter 4); [2]Only observed in 2014 season (Chapter 5); [#]Statistically comparable with CT and HINiT

Even though the broad spectrum herbicide glyphosate controls many weed species (Norsworthy 2008), its application across the entire experimental site did not allow the separate testing of herbicide effect. However, in both cropping seasons, grass weed species were less prevalent than broadleaved weeds. Grass weeds were, therefore, presumably controlled by the pre-cultivation herbicide application, as also reported by Ewald & Aebischer (2000). Total weed biomass across seasons was dominated by broadleaf weed species and highly related to HINiT cultivation. This is contrary to several author reports relating broadleaf weed species prevalence more to CT (Froud-Williams *et al*., 1983b; Tuesca & Puricelli, 2007; Tuesca *et al*., 2001). Plant residue cover under HINiT may perhaps have protected weed seedlings from herbicide, as reported by Sadeghi *et al*. (1998), while follow-up soil movements created by HINiT allowed greater broadleaf weed germination, compared specifically with CT.

The present study, like Peigné *et al.* (2007) and Winkler & Chovancová (2014), revealed that the effectiveness of cultivation systems on weed control is also much influenced understandably by weather conditions. At an early growth assessment, under relatively warm and wet conditions (Core experiment II), cultivation techniques relevance in controlling early weed growth was reduced. This is an assumption, however, as soil conditions and weeds proportions were probably compensating, as suggested by Colbach *et al*. (2006). However, under relatively cold and wet conditions (Core experiment I), the non-inversion tillage, particularly HINiT, benefited weed growth. The lower plant residue cover under HINiT possibly allowed drier and warmer

soil conditions. While, with increasing soil disturbance without soil inversion encouraged weed germination, compared with LINiT, agreeing with Teasdale (1993). In contrast, maximum tillage intensity under CT reduced weed pressure, as reported elsewhere (Clements *et al.,* 1996a; Swanton *et al.,* 2000). Furthermore, weed incidence at harvest time varied across cropping seasons. Dry weather conditions (Core experiment I) seem to encourage the natural decay of weeds prior to harvest time, possibly reducing the initial tillage effects on weed growth, as reported elsewhere (Jørnsgård *et al*., 1996; Mas & Verdú, 2003; Santín-Montoyá *et al.,* 2014). Nevertheless, under relatively wet and warm conditions prior to harvest time (Core experiment II), weed growth appears to have been encouraged. Those conditions revealed that CT is highly effective in controlling weeds, compared with non-inversion tillage systems, agreeing with others (Gruber *et al*., 2012; Usman *et al.,* 2013) and even whithout herbicide applications as reported by (Vijaya Bhaskar *et al.,* 2014b).

The core experiments results (Chapter 4 & 5) showed an inverse relationship between high weed prevalence and crop performance, as reported previously by Clements *et al.* (1996a) and Stevenson *et al.* (1997). However, the present study was unable to relate that weeds alone were the only yield limiting factor. Gruber *et al.* (2012) reported that even though a high weed density was observed there was no evidence that weeds alone were restricting main crop yield. However, if the present study focuses on effects of cultivation techniques on weed pressure, then as others report (e.g. Clements *et al*., 1996a; Froud-William *et al.,* 1983b; Gruber *et al.,* 2012; Hakansson, 2003; Swanton *et al*., 2000; Tørresen & Skuterud, 2002; Yagioka *et al.,* 2015), CT controls weeds better.

8.2.3. Soil mineral nitrogen

Cultivation effects on SMN have been widely reported (Gruber *et al.,* 2011; McConkey *et al*., 2002; Silgram & Shepherd, 1999; Soon *et al*., 2001). In the present study, cultivation treatments effects were variable across and within the seasons. The contrasting effects were the result of complex interactions between tillage intensity, plant N uptake, residual soil mineral N and the prevailing weather conditions (Chapter 4 & 5). Maximum tillage intensity under CT resulted in higher SMN and provided greater

plant N uptake, compared with non-inversion tillage (Core experiment II). This is probably due to increasing tillage intensity increasing organic matter breakdown and enhancing soil mineral N availability, as reported elsewhere (López-Bellido *et al*., 2013; Myrbeck *et al*., 2012; Yagioka *et al*., 2015). In contrast, greater plant residues and relative wet conditions under non-inversion tillage (Core experiment II) may have resulted in immobilisation and/or slow release of N, agreeing with Alvarez *et al*. (1995) and López-Bellido *et al*. (2013).

Under dry season conditions (Core experiment I), however, LINiT resulted in a higher SMN content compared with CT. The drier conditions perhaps limited the soil microbiota reducing N mineralisation, as reported by Jenkinson *et al*. (1987) and Rasmussen *et al*. (1998). Additionally, the lower plant populations under LiNiT probably left greater residual soil N, agreeing with others (e.g. Brennan *et al*., 2014; Riley, 1998; Thomsen & Sørensen, 2006). These conditions, therefore, resulted in greater SMN content under LINiT in the drier season.

The present study revealed that maximum tillage intensity, under CT, increases N mineralisation and increased the soil mineral N content. However, under dry weather conditions this study suggests that LINiT can potentially allow high SMN content, mainly due to increases in residual N allowing more N availability to the crop.

8.2.4. Energy consumption and economic impact

The present study shows that high energy inputs and production cost can still be efficient and financially worthwhile if the final output of grain yield can compensate for the inputs applied (Chapter 7), agreeing with Borin *et al*. (1997) and Küsterman *et al.* (2013). This was observed under CT when high grain yield improved energy efficiency, productivity, and gross margin - compared with non-inversion tillage systems (2014 cropping season). In contrast, when higher energy output and production value was combined with low energy input and production costs, greater energy productivity and final gross return was obtained under LINiT, compared specifically with HINiT (2013 cropping season), as also reported by Alhajj-Ali *et al.* (2013) and Knight (2004).

In conclusion, CT can potentially be energy efficient and economically viable. However, this study shows that LINiT gave promising results as an alternative practice to CT, in terms of better energy-use and reliance on non-renewable sources even with low rate of herbicide application.

8.3. Nitrogen fertilisation

8.3.1. Wheat performance

Mineral N fertilisation influences on cereal growth and development, and final grain quantity and quality have been widely studied (Cossani *et al.,* 2009; Gooding & Davies, 1997; López-Bellido *et al*., 1998; Ottesson *et al*., 2008). The present study confirmed that N fertilisation increases crop height, particularly when comparing unfertilised conditions to the application of 210 kg N ha^{-1}, agreeing with Lloveras *et al.* (2001) and Sourour *et al.* (2014). However, these increases in crop growth were not always translated into greater yield. Several explanations and suggestions have been given for the mineral N fertilisation effects on spring wheat production in each core experiment (Chapter 4 & 5). Table 8.3 summarises key findings for N fertilisation treatments in all core experiments.

Mineral N fertilisation positively affected the production of grains per ear across core experiments, with increasing grain number per ear with up to 140 kg N ha^{-1}. This response with increasing N availability agrees with Alijani *et al*. (2012) and Ferrise *et al.* (2010). Several studies also report a positive correlation between grain number per ear and final grain yield (Halvorson *et al.,* 2001; Wang *et al.,* 2014), although this was not always observed in the present study. The N fertilisation effect on crop yield across core experiments was the result of interactions with prevailing weather conditions, particularly rainfall, and the residual soil N content, as also reported by Corbeels *et al*. (1998) and López-Bellido *et al.* (2012).

Table 8. 3. Key findings for different nitrogen fertilisation treatments for all core experiments

	N0	N70	N140	N210
Tiller production	[1]Low	[1*]Comparable	[1+]Comparable	[1]High
Plant height	Low	Medium	[1#]Comparable / High	High
Ears number	Statistically not significant			
TGW	High	Medium	Medium	Low
Number of grains per ear	Low	[1]High / [2]Low	High	High
Grain yield	[2]Low	[2]Low	[2]High	[2]High
SMN	Highly low	Low	Medium	High

[1]Only observed in 2013 season (Chapter 4); [2]Only observed in 2014 season (Chapter 5); [*]Statistically comparable with N0 and N140; [+]Statistically comparable with N70 and N210; [#]Statistically comparable with N70 and N140

Increasing rainfall amount, particularly during winter months, can potentially increase soil N leaching and diminish soil N content (Core experiment II), as also reported by ADAS (2014), Halvorson *et al.* (2001) and Lloveras *et al.* (2001). Under these conditions of low SMN levels adding extra mineral N fertiliser, particularly up to 140 kg N ha^{-1} increased crop grain yield (Core experiment II), as reported elsewhere (Abad *et al.,* 2005; Alijani *et al.*, 2012; Halvorson *et al.,* 2001; Wang *et al.*, 2014). Limited rainfall conditions and the occurrence of drought events across the cropping season (Core experiment I) showed that N fertilisation failed to encourage crop yield gain as higher soil mineral N was accumulated, which was perhaps enough to boost grain yield, as mentioned elsewhere (Abad *et al.,* 2005; Corbeels *et al.,* 1998; Miao *et al.,* 2015; López-Bellido *et al.,* 2000).

Despite the N fertilisation effect on grain yield, the present study revealed that grain protein content increased with up to 210 kg N ha^{-1}. Higher N rate, therefore, is required to increase grain protein rather than to increase grain yield, agreeing with Garrido-Lestache *et al.* (2004) and Godfrey *et al.* (2010). Additionally, in all core experiments, increasing the aboveground N relative to grain yield response reduced the efficiency in use of N, as Huggins *et al.* (2010) also reported.

One of the objectives of the present study was to evaluate spring wheat productivity under different mineral N fertilisation rates. The study confirms that spring wheat

response to N fertilisation may be absent if the accumulation of mineral N in the soil is substantial, as observed during a dry season on this particular soil type and location. However, under low soil N accumulation, the application of up to140 kg N ha^{-1} seems to support greater crop need by increasing grain yield.

8.3.2. Weed pressure

Across all core experiments, N fertilisation significantly affected weed growth which is consistent with other studies (Blackshaw *et al.,* 2005; Jørnsgård *et al.,* 1996; Moss *et al.*, 2004; Lal *et al.,* 2014; O'Donovan *et al.,* 1997). Table 8.4 shows trends in N rates effect on weed infestation across the experiments. Overwinter assessment in 2013 showed greater weed occurrence under high N conditions with increasing N availability, as also reported by Bergkvist (2003).

Table 8. 4. Trends in weed growth under different nitrogen fertilisation rates across core experiments

	N0	N70	N140	N210
2013 overwinter weeds	Low	Low	High	High
Early total weed	Statistically not significant			
Mid-season total weed	Low	High	High	High
Broadleaf weed species	Low	High	High	[1]Low / [2]High
Grass weed species	Statistically not significant			
Weed prevalence (from early growth assessments to harvest)	[2]Low	[2]High	[2]High	[2]High

[1]Only observed in 2013 season (Chapter 4); [2]Only observed in 2014 season (Chapter 5).

In addition to being influenced by N, weed growth and prevalence are also affected by weather conditions influencing agricultural management effects on weed species, as reported by Peters *et al*. (2014). This was observed at early crop growth assessments when weather conditions seem to be more relevant than the N fertilisation effect. Dry weather conditions later in the season (Core experiment I) reduced weed biomass at harvest time, diminishing the N fertilisation effect. However, under wetter weather

conditions, N fertilisation increased weed prevalence compared with unfertilised conditions, as observed in the Core experiment II.

In terms of weed species, the present study showed that N fertilisation caused shifts in weed species. This was observed on the dominant species, *Stellaria media* L. and *Sinapsis arvensis* L., which were advantaged under N-rich conditions, agreeing with others (Maskell *et al*., 2010; Stevens *et al*., 2010; Storkey *et al*., 2012).

If the focus is on N influences on weeds, mineral N fertilisation greatly increased weed growth. Nevertheless, this appears not to have affected final grain yield, as both the main crop and weeds increased their growth with N, as also reported by Jørnsgård *et al.* (1996) and O'Donovan *et al.* (1997).

8.3.3. Soil mineral nitrogen

In all core experiments, differences between N rates were initially marked, but decreased with time as a result of a proportional balance between N supply and crop N consumption, agreeing with Fuentes *et al*. (2003). The present study showed that application of mineral N increases SMN content, as widely reported elsewhere (Angás *et al*., 2006; Giacomini *et al*., 2010; Glendining *et al*., 1996; Liebig *et al*., 2002; Lu *et al*., 2010; Zhao *et al*., 2014).

8.3.4. Energy consumption and economic impact

The present study showed that the application of N fertiliser decreased energy efficiency, as the N application itself is also highly energy consuming, agreeing with Deike *et al.* (2008) and Safa *et al.* (2011). In addition, even when N fertilisation significantly increased the total production value, high production costs resulted in no greater gross margin compared with zero N. The present study, therefore, confirms that despite the final grain yield produced, N mineral fertilisation gives no great efficiency in energy-use and it does not always ensure higher economic returns.

8.4. Legume undersowing

The practice of undersowing legume species has been widely adopted (Fujita *et al.,* 1992; Shafi *et al.,* 2007; Thorsted *et al.,* 2006), due to their ability to fix atmospheric N (Bakht *et al.,* 2009; Kumar & Goh, 2002). The evaluation of overwinter growth in the present study showed that black medic (BM) and white clover (WC) undersown species have a slow growth pattern (Core experiment II), agreeing with Döring *et al*. (2014) and Moss *et al.* (2004).

The present study also used undersown BM and WC in order to evaluate their weed suppression effect and potential to encourage spring wheat production. Dry and warm conditions at the time of broadcasting the undersown legume species appeared to reduce legume establishment in all core experiments. Poor establishment and slow growth of the legume species, however, seem to diminish any undersowing effects on weed control and on the wheat performance (Chapter 4 & 5). If the focus is on cereal-legume bi-cropping, therefore, then this study alone cannot recommend inclusion of BM and WC for greater weed control and to encourage wheat production.

8.5. Interactions

Several authors (e.g. Alijani *et al*., 2012; López-Bellido *et al*., 2000) have reported interactions between cultivation techniques and N application on final grain yield. The present study shows, however, that grain yield was not greatly influenced by treatment interaction, despite of some small significant interactions between tillage practices and N on the mid-season wheat biomass. The present study revealed that cultivation techniques and N fertilisation were more important in defining final grain yield than their interactions, also agreeing with Feng *et al.* (2014).

8.6. Concluding remarks

> Conventional tillage can create a more uniform seedbed allowing better plant germination and crop establishment.

➢ Grain number per ear appears to be highly related to final grain yield of spring wheat under the contrasting cultivation techniques operations examined.

➢ Rainfall patterns can markedly affect spring wheat production under different cultivation techniques. The ability to save soil moisture under limited rainfall conditions can compensate for limited crop establishment and growth under low intensity non-inversion tillage, and result in similar grain yield to conventional tillage. Under high rainfall (> 300 mm) across the cropping season, non-inversion tillage can be detrimental, and cannot ensure high grain yield of spring wheat.

➢ Soil mineral N increases under conventional tillage. However, under drier conditions limiting N mineralisation, soil mineral N content is the result of the residual N left by the plants which is indirectly affected by cultivation techniques.

➢ Non-inversion tillage systems increase weed biomass, particularly broadleaf weed species under high intensity non-inversion tillage, even when herbicide is previously applied. Non-inversion tillage systems perhaps require higher herbicide rates to control weeds but in order to reduce resilience on non-renewable inputs as herbicides, these tillage systems probably need to be complemented with others management practices such as using cover crops and wider rotations.

➢ Regardless of the energy inputs and production cost, energy efficiency and economic return under contrasting cultivation techniques mostly depend on the final grain yield produced. Conventional tillage can be energy efficient and economically viable if high yield is ensured, despite considerable energy consumption and cost. Non-inversion tillage systems can save energy and production costs.

➢ Mineral N fertilisation effects on grain yield production are also indirectly affected by weather conditions affecting soil mineral N accumulation. In

conditions of high residual soil mineral N further crop response to N fertilisation can be limited.

➤ N fertilisation increases grain protein content separate to grain yield responses.

➤ Application of mineral N fertiliser boosts soil mineral N content, confirming what is already a well known relationship.

➤ Crop canopy and weed growth are highly advantaged with mineral N fertilisation, although increasing weed growth does not always seem to reduce final grain yield.

➤ Mineral N fertiliser application is no more efficient in energy-use, and can be no different in total economic bottom-line benefit to unfertilised environments, even when higher final grain yield is produced.

➤ Undersowing black medic and white clover in dry conditions can have no effect on spring wheat productivity or weed control.

8.7.Implications

➤ Transition of soil management agricultural practices towards reduced tillage systems is promoted by the European Union Common Agricultural Policy (CAP) and the United Nations Environment Programme (UNEP) to increase food security and profits while enhancing resource-use and sustaining productivity, and as being more resilient to climate and weather variability. The present study findings show that this may be possible for spring wheat on clay soil in dry years. Low Intensity Non-inversion Tillage (LINiT), even though it can result in low crop establishment, can allow the cereal crop to compensate without loss of grain yield. However, in conditions of high rainfall (>300 mm during cropping season), LINiT can disappoint due to low establishment and poor crop growth, and a high loss in yield caused by great variability of seedbed conditions, less soil N and greater weed pressures.

- In connection with the previous implication, the UK Climate Projections (2009) suggests that the UK is likely to undergo hotter and drier summers, and warmer and wetter winters, with increasingly occurrence of extreme weather events such as dry spells, heat waves, heavy rain and flooding (Jenkins *et al.,* 2009). The present study findings, therefore, indicate that reduced tillage systems such as Low Intensity Non-inversion Tillage (LINiT) can potentially be the best option to ensure yield production and adaptability to these climate change scenarios under drier season conditions. This is particularly important as the interest of farmers for adapting agricultural practices to climate change mitigation has been growing in the last decades (Gonzalez-Sanchez *et al*., 2015; Olesen *et al.,* 2011; Peigné *et al.,* 2015; Rochecouste *et al.,* 2015).

- Several agri-environmental policies focus directly or indirectly on the reduction and greater efficiency of use of N fertilisation (United Nations Framework Convention on Climate Change; National Emissions Ceiling Directive; European Common Agricultural Policy; UK Nitrate Directive; UK Water Framework Directive). This study shows that mineral N fertilisation fails to improve final grain yield under dry seasons while, under conditions of more water availability, yield can be potentially increased. N application could perhaps be saved by foliar applications at a different timing when, and if, weather conditions are disadvantaged - with N fertilisation being more energy consuming and less economic compared to unfertilised practices.

8.8. Future work

- The variability of the responses to agricultural management practices used in the present study was the result of contrasting weather patterns across seasons. As this study was limited to only two cropping seasons, further study would be highly beneficial to a greater understanding of these cultivation techniques, N fertilisation and undersowing legumes effects on spring wheat productivity in the longer term. In addition, it would be useful to also evaluate the effects of the

agricultural management practices adopted under different soil types and weather conditions.

➢ Crop responses to water stress were mentioned throughout the thesis as a key factor affecting crop yield. How much of an influence crop root system growth and its water uptake within different seedbed conditions needs more detailed examination, and also these influences have on final grain yield also needs to be further considered.

➢ A further study of cultivation techniques and N fertilisation interaction effect on soil N leaching would also help to better explain N flow throughout the soil. In addition, the use of ^{15}N isotope labelling fertiliser method has been reported elsewhere as the most accurate method to evaluate both the soil N and N fertiliser relative contributions to plant N-uptake (López-Bellido *et al*., 2012). It could also be beneficial, therefore, to undertake a further study using isotope labelling to clarify the N fertiliser contributions to effective plant uptake.

➢ This study could not evaluate potential interactions between cultivation techniques and herbicide application on weed control. Further study would be useful to determine how much of an effect these management practices have on weed infestation. Besides continuous changes in agricultural practices modifies weed community dynamics (Santín-Montanyá *et al.,* 2014). It would be useful to also evaluate changing farm management practices influences on weed species diversity for the longer term.

➢ During this study, it was not possible to more fully explore undersown legume effects on weed control and wheat performance. A further study designed specifically to evaluate broadcasting and drilling methods for establishing a greater range of undersowing species with spring wheat could be beneficial.

➢ In a wider future study, the measurement of soil carbon sequestration, losses of N and greenhouse gas emissions could provide further indices of sustainability of field management practices explored in the present study.

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Appendices

Appendix 1. Illustrated keys used for disease assessment

Appendix 1.1. Illustrated key for leaf rust of wheat.

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Appendix 1.2. Illustrated key for septoria leaf blotch of wheat.
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Appendix 1.3. Illustrated key for take-all disease of wheat

Appendix 2. Weed species biomass across core experiments

Appendix 2.1. Grass weed species for the 2013 core experiment

	Grass weed species	Mean DM (kg ha^{-1})
1.	*Avena fatua*	170.0 ± 47.20
2.	*Lolium perenne*	116.0 ± 19.40
3.	*Alopecurus myosu.*	19.90 ± 3.01
4.	*Avena sativa*	0.412 ± 0.294
5.	*Hordeum vulgare*	0.329 ± 0.329

Appendix 2.2. Broadleaf weed species for the 2013 core experiment

	Broadleaf weed species	Mean DM (kg ha^{-1})		Broadleaf weed species	Mean DM (kg ha^{-1})
1.	*Stellaria media*	425.0 ± 44.7	18.	*Cirsium arvense*	2.44 ± 1.30
2.	*Fallopia convolvulus*	173.0 ± 16.20	19.	*Veronica persica*	1.39 ± 0.42
3.	*Sinapsis arvensis*	138.0 ± 28.40	20.	*Veronica hederifolia*	0.931 ± 0.33
4.	*Polygonum aviculare*	117.0 ± 15.60	21.	*Urtica urens*	0.745 ± 0.498
5.	*Galium aparine*	82.10 ± 13.20	22.	*Angallis arvensis*	0.616 ± 0.215
6.	*Aethusa cynapium*	70.90 ± 6.49	23.	*Rumex obtusifolius*	0.597 ± 0.26
7.	*Sonchus oleraceus*	37.50 ± 9.55	24.	*Sonchus arvensis*	0.597 ± 0.374
8.	*Persicaria maculosa*	33.60 ± 8.29	25.	*Lamium amplexicaule*	0.403 ± 0.182
9.	*Geranium dissectum*	13.30 ± 3.18	26.	*Fumaris officinalis*	0.366 ± 0.258
10.	*Lapsana communis*	6.53 ± 2.07	27.	*Brassica napus olifera*	0.333 ± 0.333
11.	*Sinapsis alba*	4.38 ± 2.22	28.	*Scandix pecten-veneris*	0.301 ± 0.201
12.	*Atriplex patula*	3.32 ± 1.30	29.	*Convolvulus arvensis*	0.292 ± 0.292
13.	*Galeopsis tetrahip*	3.32 ± 3.32	30.	*Rumex spp*	0.241 ± 0.241
14.	*Viola tricolor*	3.16 ± 1.17	31.	*Sonchus arvensis*	0.093 ± 0.065
15.	*Senecio vulgare*	2.98 ± 1.25	32.	*Cirsum vulgare*	0.051 ± 0.042
16.	*Capsella bursa-pastoris*	2.98 ± 2.12	33.	*Rumex crispus*	0.037 ± 0.037
17.	*Chenopodium spp*	2.84 ± 1.96	34.	*Vicia sativa*	0.005 ± 0.005

Appendix 2.3. Grass weed species for the 2014 core experiment

	Grass weed species	Mean DM (kg ha⁻¹)
1.	*Lolium perenne*	22 ± 10.7
2.	*Avena sativa*	295 ± 62.0
3.	*Alopecurus myosuroides*	3.8 ± 1.31
4.	*Hordeum vulgare*	0.204 ± 0.204
5.	*Poa annua*	0.0556 ± 0.0556

Appendix 2.4. Broadleaf weed species for the 2014 core experiment

	Broadleaf weed species	Mean DM (kg ha⁻¹)		Broadleaf weed species	Mean DM (kg ha⁻¹)
1.	*Aethusa cynapium*	3.75 ± 0.643	13.	*Polygomun aviculare*	1.23 ± 0.462
2.	*Persicaria maculosa*	30 ± 12.70	14.	*Cirsium vulgare*	0.171 ± 1.39
3.	*Galium aparine*	162 ± 31.70	15.	*Rumex crispus*	0.606 ± 0.31
4.	*Stellaria media*	167 ± 25.80	16.	*Veronica agrestis*	4.94 ± 1.35
5.	*Sinapsis arvensis*	385 ± 60.90	17.	*Sonchus arvensis*	2.78 ± 0.943
6.	*Veronica persica*	6.4 ± 6.20	18.	*Brassica nigra*	0.102 ± 0.102
7.	*Geranium dissetium*	18.1 ± 4.88	19.	*Viola arvensis*	0.37 ± 0.48
8.	*Lapsana communis*	11.7 ± 3.22	20.	*Myosotis arvensis*	0.0648 ± 0.0437
9.	*Sonchus arvensis*	4.75 ± 2.01	21.	*Lapsana communis*	2.60 ±1.65
10.	*Fallopia convolvulus*	4.15 ± 0.91	22.	*Atriplex patula*	3.36 ± 3.07
11.	*Convolvulus arvensis*	3.66 ± 2.01	23.	*Senecio vulgare*	1.49 ± 0.627
12.	*Phalaris paradoxa*	0.648 ± 0.468	24.	*Cirsium arvense*	2.37 ± 1.14

Appendix 3. Data set for meta-analysis

Appendix 3.1. Organic study used

Reference	Crop	Tillage treatments	Seasonal rainfall (mm)
Vijaya Bhaskar *et al.* (2013b)	Spring wheat (2012)	CT, HINiT and LINiT	589.1

Appendix 3.2. Data set with spring wheat yield (t ha^{-1}) under contrasting cultivation techniques across experiments

	2012	**2013**	**2014**
CT	3.52	5.09	5.12
HINiT	2.96	5.1	1.89
LINiT	2.11	6.2	2.28
Mean	2.86	5.46	3.10
SED	0.152	1.132	0.233

Appendix 3.3. HINiT weighed yield against CT

Seasonal rainfall type	**Tillage**	**Weighed yield (t ha^{-1})**	**SED**
<300 mm	HINiT	0.009	1.132
300-500 mm	HINiT	-3.23	0.233
>500	HINiT	-0.56	0.152

Appendix 3.4. LINiT weighed yield against CT

Seasonal rainfall type	**Tillage**	**Weighed yield (t ha^{-1})**	**SED**
<300 mm	LINiT	1.11	1.132
300-500 mm	LINiT	-2.84	0.233
>500	LINiT	-1.41	0.152

Appendix 4. Energy balance

Appendix 4.1. Amount of inputs in all core experiments

Inputs	Quantity per unit	Inputs	Quantity per unit
Human labour (h ha^{-1})		**Diesel fuel (l ha^{-1})**	
CT	1.97	CT	38
HINiT	2	HINiT	34
LINiT	1.58	LINiT	24
BM	1.5	BM	0
WC	1.5	WC	0
Nus	0	Nus	0
N0 application	0	N0 application	0
N70 application	0.8	N70 application	2.4
N140 application	0.8	N140 application	2.4
N210 application	0.8	N210 application	2.4
Herbicide spraying	0.4	Herbicide spraying	1.2
Harvesting	1.05	Harvesting	23
Machinery (h ha^{-1})		**Fertiliser (kg ha^{-1})**	
CT	1.97	N0 application	0
HINiT	2	N70 application	70
LINiT	1.58	N140 application	140
BM	0	N210 application	210
WC	0	**Herbicide (kg ha^{-1})**	2
Nus	0	**Seeds (kg ha^{-1})**	
N0 application	0	Wheat	200
N70 application	0.8	BM	8
N140 application	0.8	WC	7
N210 application	0.8		
Herbicide sprayer	0.4		
Harvesting	1.05		

Appendix 4.2. Specification of all machinery used in all core experiments

	Tractor type	Implement type	Implement width (m)	Working depth (cm)	Speed of work (km h⁻¹)	Work rate (ha h⁻¹)	Time (h ha⁻¹)	Fuel (L ha⁻¹)
CT	MF 5465 (120 HP, 4wd) (5080 kg)	5 furrow Kverneland plough + press	1.8	20	7	1	1	23
		Power harrow seed drill	3	8	8	1.7	0.97	15
HINiT	TM 155 (154 HP, 4wd) (5642 kg)	2 passes of ST bar attached Simba X-press	3	25 & 12	10	1.2	1.4	28
		Vaderstadt with seed drill	4	8	10	2.8	0.6	6
LINiT	TM 155 (154 HP, 4wd) (5642 kg)	1 passes of ST bar attached Simba X-press	3	25 & 12	10	1.2	0.7	14
		Eco-dyn seed drill	3	26	9	1.9	0.88	10
Fertiliser sprayer		2 passes CASE IH SP3000 (150HP)	6				0.8	2.4
Herbicide sprayer		CASE IH SP3000 (150HP)	6				0.4	1.2
Harvest combine							1.05	23

Appendix 5. Publications prepared during this investigation

Vijaya Bhaskar, A.V., Rial Lovera, K., Davies, W.P. & Cannon, N.D. (2014). Weed prevalence under organic and low input cultivation systems. *Aspect of Applied Biology*. Agronomic decision making in an uncertain climate. 125, 129-134.

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