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Cultivation regimes and legume cover crops for organic wheat (Triticum aestivum) production

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Cultivation regimes and legume cover crops for organic wheat (*Triticum aestivum*) production

BY

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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 any comparable academic award elsewhere.

Vijaya Bhaskar.A.V.

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Abstract

Field trials were conducted in 2010/11, 2012 and 2013 at the Royal Agricultural University's Soil Association certified organic Harnhill Manor Farm, Gloucestershire, UK (NGR SP 075 006), to investigate suitable cultivation techniques and legume cover crops for winter and spring wheat production. Cultivation treatments included conventional tillage (CT), low residue non-inversion tillage (LRNiT) and high residue non-inversion tillage (HRNiT) as main plots while undersowing white clover (WC), black medic (BM) or no undersowing (N_{us}) as subplots. Wheat establishment, growth, grain yield and weeds infestation were assessed to determine the feasibility of these husbandry techniques. For winter wheat in 2010/11, LRNiT seems to be an acceptable alternative for CT. However, for spring wheat in 2012 and 2013, CT seems to be more reliable management option. The performance of undersown legumes was highly weather reliant and inconsistent in the seasons studied.

Plant establishment and the succeeding yield parameters were positively related to grain yield. CT had significantly higher plant establishment than LRNiT or HRNiT in each season. For winter wheat, the competition and compensation on shoot density among CT and LRNiT did potentially outweighed cultivation-induced effects on plant establishment. This condition resulted in statistically equivalent crop growth and yields with LRNiT to that of CT. In contrast, for spring wheat in 2012 and 2013, CT that had significantly higher plant establishment also resulted in better crop growth and greater grain yields than other cultivation treatments. In all seasons, HRNiT had significantly lower plant establishment and also reduced grain yields, compared with LRNiT or CT. More soil cultivation also significantly reduced total weeds than less tilled soil such as HRNiT. On the basis of weed species, significantly higher broadleaf weeds were present under CT and significantly higher grass weeds were present under HRNiT.

Out of three investigated years, legume cover crops effects were clearly observed only in 2012 with spring wheat. More vigorous growth of WC showed a significantly inverse relationship with broadleaf weeds and total weeds, compared with slow growing BM. This situation, resulted in non-significant yield components or grain yield reduction, compared with non-undersown spring wheat. In this context, white clover seems to be more suitable legume cover crop than black medic.

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Abbreviations

ADAS	Agricultural Division of Advisory Service
BM	Black medic
^{o}C	degree Celsius (centigrade)
C_{org}	Soil organic carbon
cm	centimetre
CT	Conventional tillage
DEFRA	Department for Environment, Food, and Rural Affairs
DM	dry matter
GS	growth stages
HGCA	Home-Grown Cereals Authority
HRNiT	High residue non-inversion tillage
h	hours
ha	hectare
K	Potassium
kg	kilogram
MPa	Mega Pascal
kPa	kilo Pascal
L	Litre
LRNiT	Low residue non-inversion tillage
MJ	megajoule
mg	milligram
ml	millilitre
mm	millimetre
N	Nitrogen
NIAB	National Institute of Agricultural Botany
NGR	National Grid Reference
NO_3-N	Nitrate nitrogen
NH_4-N	Ammonium nitrogen
N_t	Soil total nitrogen
N_{us}	Non-undersown
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 weights
UK	United Kingdom
WC	White clover
§	Section symbol

Chapter - 1

BACKGROUND TO THE STUDY

1.1 Introduction

Food security is one of the fundamental human rights (UN 1948). In the last 50 years, regardless of the growth and development in the social economy, malnourishment and starvation still predominates (FAO 2013). Continuing agricultural yield increases are mostly taken up by rapid population growth (Fuglie *et al.* 2012). The possibilities for expanding food production reportedly include additional arable land, improvement of soil quality and more intensified production per unit land area (Cakmak 2002). However, the ultimate need for food required by the rising human population is eventually restricted by the accessibility of suitable land (Wackernagel *et al.* 2006). The introduction of the so-called Green Revolution in the late 1960s was an attempt to increase crop productivity rather than increasing the land area for production (Borlaug 2007). Indeed, the Green Revolution has increased crop yields and doubled global cereal production in the past 40 years (Tilman *et al.* 2002). However, intensification of production transformed local and traditional agriculture to global industrialised systems, where external farm inputs such as fuels, fertilizers, and pesticides are often substituted for functional ecosystem services (Pimentel *et al.* 1973; Cassman 1999). This transformation, although, provided greater control of crops, it often reported to carry ecological and social consequences, including soil degradation; increased nutrients in water sources; pesticide positioning; bio-diversity loss and negative contribution to the change in global climate system (Lin *et al.* 2008; Tilman *et al.* 2002). Increasing concerns recently over these impacts has led to the development of conservation agriculture practices.

Conservation agriculture strategy combines natural regulation mechanisms and farming system components to achieve maximum replacement of external farm inputs (Vereijken 1992). Consequently, conservation agriculture recommend diverse crop rotations, minimum soil cultivation, cover cropping, disease resistant cultivars, targeted application of nutrients and pesticides, and promotion of biodiversity (Jordan *et al.* 1997). These practices, thus far, have only marginally contributed to the lessening of the negative ecological impacts of industrialised conventional agriculture (Stoate *et al.* 2009). However, restoring environmentally sound, sustainable cropping systems is probably the biggest challenge for the current agricultural research. Integration of organic farming (Kirchmann *et al.* 2002) and conservation agricultural practices (Hiltbrunner *et al.* 2007a) such as non-inversion tillage and the use of legume cover crops are thought to be key strategies for meeting these challenges.

According to Neufeldt (1988), sustainability is the ability to 'keep in existence; keep up; maintain or prolong. Organic farming has been recommended as a way to improve the sustainability of agro-ecosystem by reducing the use of chemical inputs and non-renewable resources (Naudin *et al.* 2010). Under organic farming, limitations on the use of agro-chemicals promote intensive tillage for nitrogen mineralisation and weed control (Chamen & Parkin 1995). Nevertheless, frequent tillage can lead to depletion of organic matter and proneness to erosion (Stoate *et al.* 2009). In contrast, a conservation agricultural strategy such as non-inversion tillage and the use of legume cover crops is gaining interest in UK in the context of organic farming because of the many potential benefits such as faster land preparation; reduced weed infestation; improved soil structure and stability which can increase soil moisture content, lower compaction and also resist soil erosion (Baker *et al.* 2002; Derpsch *et al.* 2010; Vakali *et al.* 2011). These changes in soil environment could also possibly improve the functioning of cropping systems by increasing water holding capacity and enhancing nutrient conservation specifically soil mineral nitrogen (Franzluebbers 2002; Holland 2004).

Until very recently, conservation agricultural strategies have been developed more successfully for conventional farming systems. Translating these practices to organic farming has been (and still is) a major challenge because of the limitation on the use of synthetic chemicals and mineral fertilizers (Berry *et al.* 2002; Bond & Grundy 2001; Vakali *et al.* 2011). As crop rotation is traditionally an important aspect of organic cropping systems, this thesis focuses on investigating various farm management practices from full inversion to low or high residue non-inversion soil tillage and the inclusion of legume cover crops either as bi-crops or green manures. The feasibility of these techniques will be assessed based on the field and yield performance of winter or spring wheat. These investigations may help to highlight the agronomic challenges and promising outcomes of adopting different crop husbandry systems, with the intention of creating and further developing a more sustainable farming approach within the organic sector.

1.2 Organic farming

Organic farming often described as ecological and biological farming systems (IFOAM 2008). Organic agriculture relies on a number of alternative husbandry practices that take full advantage of ecological cycles to overcome the potential problems caused by the limitation in use of agrochemicals and fertilisers (Lampkin 2002). In organic farming systems, soil fertility is enhanced by crop rotation, cover cropping, and mulching (Pimentel *et al.* 2006). Pest control can be achieved by using appropriate cropping techniques, biological control, and natural pesticides (mainly extracted from plants) (Birkhofer *et al.* 2008). Weed control is managed by appropriate rotations, mechanical cultivation, seeding timing, mulching and transplanting (Lotter 2003; Altieri & Nicholls 2004; Koepf 2006; Kristiansen *et al.* 2006; Gliessman 2007). Consequently, organic farming is expected to produce superior quality food; to increase agricultural resilience; to enhance the efficiency in use of renewable resources, and to sustain soil fertility and biodiversity (Stockdale *et al.* 2001). However, there are some potential disadvantages such as requirements for additional labour and excessive cultivations as a method of controlling weeds that can also lead to soil compaction and possible erosion problems (Lampkin 1992). Loss of moisture from increased cultivations and poor nitrogen availability, along with greater weeds competition can limit the crops yield and protein quality (Offermann & Nieberg 2000; Clark *et al.* 1999). Although, the actual performance of organic farms is strongly influenced by the genotype of the crop varieties (Schjonning *et al.* 2002; Bakken *et al.* 2006) the extent to which the crop genetic potential can be expressed will mainly depend upon soil properties, agricultural management techniques and seasonal weather conditions.

1.2.1 Organic farming and crop yields

Until recently, there were very few crop varieties bred specifically for organic production, although, crop varieties perform differently at various input levels (Wolfe *et al.* 2008; Murphy *et al.* 2007). Traditionally organic growers would take much of their guidance and information from variety performance (with particular attention given to yield, quality and disease resistance) under conventionally grown trials (Li *et al.* 2010; Lammerts van Bueren *et al.* 2011). Generally, it has been reported that most European studies on crop yields under organic farming conditions tend to be lower than conventional systems (Vereijken 1989; Powtala *et al.* 1993). The Soil Association (2008) estimated that there is normally a 30% - 50% yield reduction from organic farms, but believed yields could be as high as conventional systems as long as weed pressures and nutrient inputs were adequate. Cormack (2000) and Stockdale *et al.* (2001) also reported that on average, yield from arable crops was 20% to 40% lower in organic systems. On the other hand, comparative studies in developing countries e.g. Southern Brazil revealed that organic yields were generally higher or equivalent to conventional systems under favorable conditions (Gibbon & Bolwig 2007) and significantly higher under less favourable conditions (Arshad *et al.* 1999; Bonfil *et al.* 1999; De Vita *et al.* 2007). Pretty *et al.* (2006) reported that farms initially converted to organic experienced lower yield, however, they soon recovered, and the farms became more productive than conventional systems over a long term, due to the possible improvement in soil fertility levels. Generally, crop yield comparative studies appear neither consistent nor predictable and vary across regions (Lal *et al.* 2007). Nevertheless, the crop yields under organic systems can be possibly compromised or balanced with lower input cost, enhancement in soil conditions, and higher gross margins (Pimentel *et al.* 2005).

1.3 Conservation agriculture

Conservation agriculture realises the importance of the upper 0-20cm soil layer as the most active zone, but also the zone vulnerable to soil erosion and soil degradation (Dumanski *et al.* 2006). It is also the zone where human activities of agricultural management have the most immediate, and possibly the greatest influence (Derpsch

1999; Hobbs 2007). With this outlook, conservational agricultural practices are constructed on the following agroecosystem management principles (Dumanski *et al.* 2006):

- *Maintaining permanent soil cover and promoting minimal mechanical disturbance of the soil, to ensure sufficient living and/or residual biomass to enhance soil and water conservation and control soil erosion*
- *Promoting a healthy, living soil through crop rotations, cover crops, and the use of integrated pest management technologies*
- *Promoting precision placement of crop inputs to reduce input costs, optimize efficiency of operations, and prevent environmental damage.*

Conservation agricultural principles and practices seem to comply with parameters of agricultural sustainability to a larger extent than conventional agriculture does (Derpsch *et al.* 2010). Performing these practices helps to improve soil quality. In doing so, it can reduce long-term dependency on external farm inputs; enhances environmental management and improve water use efficiency (Peigne *et al.* 2007). Additionally, conservation agricultural practices potentially reduce emissions of greenhouse gases through lowering the use of fossil fuels and can also minimises the number of cultivations, therefore saving labour and energy costs (Holland 2004; Morris *et al.* 2010). The application of these principles and practices correspond to several agronomic strategies from direct drilling through living mulches to reduced tillage with cover crop introduced between the main crops (Derpsch *et al.* 2010). The interests of soil conservation practices are often reported to be higher when these practices are fully applied together than when they are isolated (Kassam *et al.* 2009). Accordingly, adopting conservation agricultural principles and practices might possibly improve the environmental and economic performance of organic farming (Peigne *et al.* 2007; Hiltbrunner *et al.* 2007a).

1.4 Review of literature

Within this section, literature on different cultivation systems and its influence on cropping environment, soil properties and nutrient management, and also the implications of legume cover crops are reviewed. These areas were chosen mainly to recognize the prospects of different husbandry practices for organic systems to ensure long-term productivity.

1.4.1 Tillage

Tillage aims to create a soil environment favourable for seedling emergence, plant growth, and crop productivity (Atkinson *et al.* 2007). Prihar (1990) defined soil tillage as physical or mechanical manipulation of soil to alter the soil conditions by providing a favourable environment for the purpose of crop establishment and emergence. In addition, tillage potentially suppresses weeds; increases water infiltration and reduces the evaporation of soil moisture. In the UK, current tillage can be divided into two broad systems based on the intensity of soil practice and percentage of retention of soil surface plant residues: conventional tillage also known as inversion tillage and conservation tillage is known more widely within the UK as non-inversion tillage (Davies & Finney 2002).

1.4.1.1. Conventional tillage

Conventional cultivation includes both primary and secondary tillage operations to prepare a seedbed (Gajri *et al.* 2002). Primary tillage involves inverting the soil using a mouldboard plough (Schjonning & Rasmussen 2000). The mouldboard plough used today are reversible, consisting of a series of mouldboards, forward rake points, vertical plates and tail pieces attached via a leg to the coulter frame (Soffe 2003). The mouldboards are passed through the soil at a depth of around 20 to 25cm, depending upon the speed of cultivation and the soil type (Brassington 1986). In addition to primary tillage, often used form of secondary cultivation is with a power harrow in combination with seed drill (Bell 1996). Power harrow consists of vertical spiked pairs of tines each driven by a series of gears, which drives or is driven by adjacent gears, which results in neighbouring sets of tines contra-rotating (Soffe 2003). The movement of the tines is faster than the forward motion of the tractor allowing for a pulverising action upon the soil and thereby producing fine tilth seedbeds, which are smooth, level and compact (Brassington 1986). Thus both primary and secondary cultivations prepares a seedbed by incorporating all surface residue and interrupting weed, pest and disease life cycles and also providing the optimum conditions for seedling emergence (Cannell 1985; Jordan & Leake 2004).

Many farmers still rationalise the use of conventional cultivations for the ease of drilling; yield security and to loosen crusted and compacted soils (Morris *et al.* 2010). However, several studies have shown that frequent conventional ploughing can have detrimental effects on soil environment leading to soil compaction; soil erosion which in turn, can reportedly lower agronomic productivity (Unger 1979; El Titi 2003; Lal *et al.* 2007).

1.4.1.2. Non-inversion tillage

Non-inversion cultivation systems usually involve fewer passes and do not invert the soil as with conventional tillage (Carter *et al.* 2003a). The implements associated are tines and disc harrows that work at a shallow depth, such that crop residues are mixed into the topsoil, but leave a proportion on the soil surface (Christian 1994). The tines available in the UK comes with different shapes and with different angles from straight to curved and either fixed (rigid) or moving (spring) with front boards attached to mounted sections (Christian 1994). The tines provide initial breakdown of surface and residue. In addition, the loosening tines also help clear trash and remove compacted soil layers (Morris *et al.* 2010). These are followed by shallow working disc harrow roughly at around 12 to 15cm depth, depending upon speed of cultivation and the soil type (Soffe 2003). The disc harrow consists of two to four adjustable axles each with a number of concave discs mounted along its length suited for added mixing and cultivation (SMI 2003). Axles are angled for forwards motion with front axle discs cutting and throwing soil outwards, while rear axle discs throw soil inwards (SMI 2003). The press wheels that are usually mounted at the rear of the cultivator firm and level the surface prior to seed drilling (Morris *et al.* 2010). Throughout the process, the loosening tines, and compact disc harrow with an integrated press roll, combines high speed shallow cultivations with effective consolidation. Drilling usually requires a high output cultivator drill that uses a combination of discs and tines ahead of the seed coulters to assist seed depth and emergence (Bell 1996). Thus, less soil movements without inversion creates a seedbed condition, and soil physical environment that mechanical impedance and aeration do not restrict root growth (Cannell 1985). In the process, non-inversion tillage reduces energy and facilitates faster land preparation allowing a large area to be sown within the optimum time frame (Ball 1989). Additionally, non-inversion tillage tends to be more environmental friendly since soil erosion is being reduced, due to improved aggregate stability and remains of soil surface crop residue (Stagnari *et al.* 2009; D'Haene *et al.* 2008). Furthermore, non-inversion tillage reportedly improves the soil quality by increasing carbon sequestration although; benefits are mainly confined for the topsoil (Berner *et al.* 2008; Govaerts *et al.* 2010; Stockfisch *et al.* 1999; Lal & Kimble 1997).

1.4.1.2.1 Value of retaining soil surface crop residues

Non-inversion tillage usually associated with retaining considerable amount of crop residues on the soil surface (Geerse 2010). Crop residues reportedly play a key role in soil and water conservation, maintenance of soil properties, regulate the growth of weeds, and possibly improve subsequent crop performance (Power *et al.* 1986; Unger *et al.* 1991). Other potential benefits reported include: an increase of organic matter and nutrient levels; moderation of soil temperature and increased soil biological activity - all of which are essential for assisting crop production (Powell & Unger 1997). The use of crop residues as a soil modification, however, is often limited due to its interruption to mechanical tillage (Siemens *et al.* 2004). Reduced crop yields are often reported due to poor seed-soil contact, uneven sowing depth, and seeding row space when either drilling or cultivating into surface residue conditions (Siemens & Wilkins 2006; Sprague & Triplett 1986). Despite possible benefits of maintaining soil surface crop residues under non-inversion tillage; the residue needs to be checked effectively to ensure minimal interference to seedling germination but to maximize soil protection (Kaspar & Erbach 1998).

1.4.2 Tillage effects on soil properties

Tillage is considered necessary to conserve or enhance soil properties (Aziz *et al.* 2013). Change in tillage intensity often results in differences in soil physical, chemical, and biological properties which in turn, result in changes to the functional quality of soil (Derpsch *et al.* 2010; Celik *et al.* 2011; Ding *et al.* 2011).

1.4.2.1 Physical properties

Levels of tillage intensity may cause temporal change to the soil physical environment (Rasmussen 1999). However, the actual effects reportedly depend on several factors such as soil properties, climatic conditions, history of cultural management including the type and extent of cultivation practiced (Mahboubi *et al.* 1993; Blevins *et al.* 1983a). The major soil physical properties that are normally affected by change in tillage intensity are soil bulk density and penetration resistance.

Bulk density has a major influence not only on the dynamics of water and air in soil, but also on the root growth of crops (Unger & Cassel 1991). Generally, all tillage practices reportedly reduce soil resistance to the depth of loosening (Erbach *et al.* 1992). However, several previous experiments were investigated to compare non-inversion tillage with conventional. Non-inversion tillage, often reported to have higher bulk density especially in the upper 0-15cm soil depth (Tollner *et al.* 1984; Kaspar *et al.* 1991; Blevins *et al.* 1983a). However, some research showed that soil bulk densities with non-inversion tillage are usually lower than conventional tillage (Russell *et al.* 1975; Lal 1976a; Griffith *et al.* 1977). A number of researchers also report no difference in soil bulk densities between the two tillage systems (Shear & Moschler 1969; Cannell & Finney 1973). In general, Kitur *et al.* (1993); Pelegrin *et al.* (1990); Franzen *et al.* (1994); Lopez *et al.* (1996) reported that the difference in bulk density is maximal after the cultivation practices or after planting, and may possibly fall quickly during the growing season and become nearly insignificant between tillage systems at the end of the growing season. Cultivation practices also affect structural porosity, which is the result of the arrangement of clods and aggregates (Guerif *et al.* 2001). Total porosity is inversely related to bulk density (Carter & Ball 1993), which provides a measure of the porous space left in the soil for air and water movement. High porosity (low bulk density) leads to poor soil–root contact, and low porosity (high bulk density) reduces aeration and increases penetration resistance and limits root growth (Cassel 1982). In general, most of the soils reportedly have bulk density between 1 to 2gcm^{-3} and optimum bulk density varies according to soil texture and crop types (USDA 2008).

Penetration resistance is strongly influenced by soil water content and bulk density. It can reportedly increase with depth due to the increase in shaft friction (Bradford 1986; Campbell & O'Sullivan 1991). Previous studies, comparing conventional and non-inversion tillage reported higher penetration resistance under non-inversion tillage, particularly in the upper 0-10cm soil depth (Ehlers *et al.* 1983; Wander & Bollero 1999; Hammel 1989; Hill 1990; Grant & Lafond 1993). However, Franzen *et al.* (1994) and Lal (1976a) observed significantly lower soil resistance to penetration under non-inversion tillage at 0-10cm soil depth due to mulching. Mahli *et al.* (1992) in their study determined soil penetration resistance seven years after contrasting soil tillage, and reported that penetration resistance was significantly higher under non-inversion tillage than conventional in the upper 0-10cm soil layer, but did not differ in the 10-20cm and 20-30cm soil layers between the tillage treatments. Similar to bulk density, the effect of tillage on penetration resistance is reported to be temporary and the soil rapidly settles, recovering its former state (Franzluebbers *et al.* 1995; Campbell & Henshall 1991). In general, soil penetration resistance greater than 2MPa reportedly reduce root growth, however, the results can vary depending on soil types and crop species (Atwell 1993).

1.4.2.2 Chemical properties

Different tillage techniques can possibly influence soil chemical properties particularly, the soil reaction (pH) and nutrient content (White 1990). Many previous studies have reported that the pH in the top soil surface layers usually decreases rapidly under non-inversion tillage, compared to conventional (Blevins *et al.* 1983a; White 1990). The pH reduction could be due to the presence of soil surface crop residues that have a tendency to accumulate organic acids formed when crop residues are broken down (Brady 1990; Blevins *et al.* 1983a).

Greater tillage intensity reportedly increases the rate of organic matter decomposition while soils that have been less tilled for several years have higher organic carbon content (Blevins *et al.* 1977). This is to do with a build-up occurring mostly in the top 0-5cm soil layers, mainly due to the fact that the crop residues are left on the soil surface rather than mechanically incorporated as with conventional tillage (Rasmussen & Collins 1991; Unger 1991). However, below a depth of 5-10cm the pattern is often reported to be reversed or no difference is observed between tillage techniques (Blevins *et al.* 1977; Mahboubi *et al.* 1993; Ismail *et al.* 1994). This is because under non-inversion tillage, most of the crop residues are left on the soil surface, rather than being mixed throughout the tilled layer. The distribution of organic nitrogen with less tilled soils reportedly follows closely to that of organic carbon (Dick 1983; Karlen *et al.* 1994a).

Less tilled soils has also been reported to maintain higher concentrations of phosphorus (P) and potassium (K) in the top soil surface layers, while conventional ploughing reported to have uniform nutrient levels throughout the tilled layer (Triplett & Van Doren 1969; Juo & Lal 1979; Ismail *et al.* 1994). Due to a lack of soil inversion, these two relatively immobile nutrients remains concentrated in the top soil layers (Triplett & Van Doren 1969; Fink & Wesley 1974; Ismail *et al.* 1994). Stratification of other nutrients such as calcium (Ca), magnesium (Mg), manganese (Mn), Iron (Fe), and zinc (Zn) have also been reported to show a similar trend to that of P and K between tillage techniques (Blevins *et al.* 1983b; Shuman & Hargrove 1985).

1.4.2.3 Biological properties

Greater biological activity has been shown to exist at the surface of less tilled soils, compared to conventional ploughing due to the reported higher moisture status and the presence of organic carbon substrate (Doran 1980). The maintenance of organic matter in topsoil is of great importance in promoting biological activity (Karlen *et al.* 1994b). Biological activity has an influence on a number of soil properties and processes including water infiltration, nutrient supply and cycling, and organic matter content (Reuter & Kubiak 2001). Joschko *et al.* (2009) reported that, tillage can affect earthworm populations directly by the mechanical tillage operations - as well as indirectly as a result of the consequent changes in the soil environment. In general, previous studies have often reported increased earthworm density and weight of earthworms under non-inversion tillage, due to more limited soil movements and continuous presence of soil surface crop residues (Edwards & Bohlen 1996; Gerard & Hay 1979; Francis & Knight 1993; Tebrugge & During 1999).

1.4.3 Tillage systems and weeds

Weeds remain one of the most significant agronomic problems associated with organic arable production (Clements *et al.* 1994a). It is sometimes said that a low weed population can be beneficial to the crops, as it provides food and habitat for a range of beneficial organisms (Fuller 1997; Millington *et al.* 1990). However, above critical population thresholds, weeds can significantly compete and reduce main crop yield and quality in both conventional (Cussans 1968; Hewson *et al.* 1973) and organic (Bulson 1996) crop production systems.

In general, environmental factors including weather condition, location, and time of year can have major impact on weed communities compared to agricultural management techniques (Derksen *et al.* 1993). Shrestha *et al.* (2002) reported that long-term changes in weed flora are driven by an interaction of several factors including tillage, environment, crop type, crop rotation and the timing and type of weed management practiced. Generally, under organic farming, ploughing remains the basic tool to deal with weeds (Elliot *et al.* 1977). Previous studies have shown that changes in tillage techniques can potentially alter the distribution, population, and composition of weeds in the soils (Buhler 1995; Ball & Miller 1993). According to Hakansson (2003) tillage can provide an effective way of manipulating or managing weeds. Tillage affects weeds by uprooting, dismembering, and burying them deep enough to prevent emergence, by changing the soil environment, and so promoting or inhibiting the weeds germination and establishment and by moving their seeds both vertically and horizontally (Clements *et al.* 1996a; Swanton *et al.* 2000). Any reduction in tillage intensity or frequency, therefore, poses serious concern for organic farmers with regard to weed management. Weed species shifts (Buhler *et al.* 1994) and losses in crop yields as a result of increased weed densities (Blackshaw *et al.* 2001a) have been cited as major reasons why organic farming with non-inversion tillage have not enjoyed more wide spread adoption.

Under conventional tillage most weed seeds that are initially near the soil surface are buried by inversion (Hakansson 2003; Colbach *et al.* 2005) whilst, under non-inversion tillage most weeds possibly accumulate on or near the soil surface and are less uniformly distributed due to the more limited soil movements without inversion (Ball 1992; Phillips *et al.* 1980). Among weed species, previous studies have found greater emergence of broad-leaved weed species under conventional rather than non-inversion tillage (Froud-Williams *et al.* 1983b; Locke *et al.* 2002). The presence of broad-leaved weeds in the ploughed field was reported to occur because non-dormant buried weed seeds were brought up annually to near the soil surface where they could germinate rapidly (Froud-Williams *et al.* 1983a). On the other hand, Hakansson (2003) reports that non-inversion tillage leads to an increase in grass weed species due to their susceptibility to mechanical disturbance which is more limited under non-inversion tillage systems. Thus the differences in tillage techniques manipulate the fate of weeds in a number of ways. With conventional tillage most of the weeds are buried and either decompose or remain in a dormant state, which is not the case with non-inversion tillage (Roberts & Feast 1972). More weed seeds are also incorporated into soil aggregates with conventional tillage rather than with non-inversion tillage, where they are less likely to germinate (Pareja *et al.* 1985). One possible advantage associated with non-inversion tillage is that weed seeds exposed on the soil surface may be more readily eaten by vertebrates and invertebrates; killed by weathering, or possibly harmed by pathogens than those buried deeper (Cromar *et al.* 1999). Nevertheless, Clements *et al.* (1996a); Pareja & Staniforth (1985); Swanton *et al.* (2000) reported that under non-inversion tillage systems 60 % to 90% (depending on the soil type) of weeds are located in shallow emergence depth, causing greater weed competition at early crop growth stages that can adversely affect later crop growth.

1.4.4 Tillage systems and diseases

Tillage effects on plant diseases are variable, depending on the soil, region, prevailing environment, crop type, and the biology of disease organisms (Bailey & Duczek 1996; Conway 1996; Sturz *et al.* 1997). According to Smiley & Wilkins (1993) differences in weather cycles, crop rotations and variety selection may account for greater differences in the impact of diseases, compared to tillage systems. Typically, non-inversion tillage is thought to have adverse effect of increasing some diseases through modification of local environment by (1.) increasing levels of residue-borne diseases and, (2.) inducing changes in the environment that include cooler soil temperatures and increased soil moisture (Bockus & Shroyer 1998; Sturz *et al.* 2000; Watkins & Boosalis 1994). For example, Sumner *et al.* (1981) reported that the inoculum to initiate *Pyrenophora tritici-repentis* (tan spot of wheat) comes directly from the infected residue left on the soil surface. Another similar example is *Gaeumannomyces graminis* var. *tritici* (take-all of wheat), where the pathogen survives in the upper root and crown tissue. If the infected residues are destroyed by conventional tillage, the inoculum is also possibly destroyed. However, if the infected residues are left undisturbed, pathogen survival and resulting disease development increases (Sumner *et al.* 1981). Take-all is also favoured by non-inversion tillage because residue conserves soil moisture and decreases soil temperature that favours take-all (Sutton & Vyn 1990). A few diseases, such as *Rhizoctonia* root rot on wheat, are favoured with non-inversion tillage not only because the fungus causing this root rot surviving on the residue, but also because of a reduction in soil disturbance (Sumner *et al.* 1981). This allows the fungus to form a large growth mat that serves as a base from which infection of wheat plants can occur. In contrast, there are a several diseases such as *Bipolaris sorokiniana* (common root rot) and various stalk rots of corn that are reduced by non-inversion tillage. This is again, often related to environmental conditions (Bailey 1996; Conway 1996; Rothrock 1992). As described, soil moisture increases and soil temperature decrease with non-inversion tillage, thereby creating unfavourable conditions to these pathogens, since they prefer drier and warmer soil environments and tend to cause the most damage under conditions of moisture stress.

1.4.5 Tillage systems and soil nitrogen availability

Levels of tillage intensity could possibly affect the mineralisation of nitrogen within the soil (Silgram & Shepherd 1999). Blevins & Frye (1993) found that less tilled soils suffer transitory nitrogen limitation due to slower soil organic matter decomposition as compared with more tilled soils. Decomposition rates are directly affected by the quantity of residue incorporation that occurs (Schomberg *et al.* 1994). Both the surface and buried residue immobilized nitrogen, but surface residue immobilized nitrogen three times longer than buried residue (Schomberg *et al.* 1994). Decomposition of surface residues is maximised in climatic conditions where relative humidity is high, warm temperatures prevails, and growing seasons are longer (Peterson *et al.* 1995). Silgram & Shepherd (1999) reported that physical disturbance by increased levels of tillage intensity often increase nitrogen mineralisation by exposing soil organic matter to greater microbial activity. In addition, the increased cultivations would also modify the soil environment (soil temperature and water content) which would increase the growth and activity of soil fauna and thus increase nitrogen mineralisation (El Titi 2003). However, the effects of increased cultivation resulting in greater nitrogen mineralisation was often found to be moderately short-lived, although, this depended much on the time of cultivation and environmental conditions prevailing during and after cultivation (Silgram & Shepherd 1999).

The presence of mixed straw residues on the soil surface can also possibly limit the availability of soil mineral nitrogen to the following crop (El Titi 2003). This is so because the mixed cereal straw residues have been reported to promote rapid immobilisation, as microbial populations are unable to satisfy their nitrogen demand from such carbonaceous substrate (Silgram & Shepherd 1999). In general, increases in soil mineral nitrogen availability due to more cultivation do not necessarily favour greater crop productivity. This is because previous studies have often reported that crop nitrogen uptake is regulated not only by soil mineral nitrogen availability but also on crop growth rate (Greenwood 1982). Additionally, there is also a possibility that the greater amounts of soil mineral nitrogen with increased cultivations were at greater risk to nitrate leaching, and might not be available during high crop demand (Silgram & Shepherd 1999).

1.4.6 Tillage systems and Crop yields

Crop yield is reportedly determined by number of interacting factors including weather conditions, cultivation techniques, and incidence of pests and diseases (Lal 1989; Cannell & Hawes 1994). Making, many previous comparative studies on crop performance are more difficult and also not predictable (Lopez-Bellido *et al.* 1996; Lal 1979). But generally, it has been reported that conventional tillage has been found to produce crop yields that are either the highest or compare very favourably with other cultivation systems and are often found to be the most consistent over seasons with varying climatic conditions (Jones *et al.* 2006).

Tillage can have positive or negative or no effect on crop yields (Lal 1991; Unger & Stewart 1976). Previous studies have reported that under conditions of favourable precipitation, adequate soil water, good drainage, and sufficient nutrient inputs, crop yield is not greatly influenced by tillage systems (Al-Darby & Lowery 1986; Christian & Miller 1986; Gerik & Morrison 1984). However, some researchers have reported increased crop yields under less tillage when conditions having shortage of precipitation and soil water (Musick *et al.* 1977; Unger & Wiese 1979; Jones 1981). Lower crop yields with less tillage have been reported in conditions receiving adequate to excessive precipitation, low soil temperatures, poor drainage, and poor weed control (Griffith *et al.* 1977; Papendick & Miller 1977; Costamagna *et al.* 1982; Hargrove & Hardcastle 1984). These conflicting results demonstrate that effects of tillage on crop yields are often inconsistent and can largely depend upon location of production, crop varieties, soil properties, and climatic factors, as reviewed by Morris *et al.* (2010) and Rasmussen (1999).

1.4.7 Tillage systems and grain protein content

Grain protein content is of great importance for the wheat industry (Wall *et al.* 1979). High protein wheat grains are required for the milling and baking industries (Mader *et al.* 2007). More than 95% of organic production is based on crop varieties bred for the conventional high-input sector (Li *et al.* 2010). Recent studies have shown, however, such varieties lack important traits required under organic and low-input production conditions (Lammerts van Bueren *et al.* 2011; Li *et al.* 2010). Some of the traits (e.g. semi-dwarf genes) that were introduced to improve yield performance and also to address problems such as lodging in cereals in conventional high-input systems were sometimes shown to have lower protein content and poor nutrient use-efficiency under organic agronomic conditions (Lammerts van Bueren *et al.* 2011; Li *et al.* 2010). Previous studies have reported that grain protein content is the result of complex interaction of a number of factors including crop varieties, soil conditions, climate, cropping practices, nitrogen availability and crop potential yield beyond tillage systems, which in many organic sector cases hinder their investigation (De Vita *et al.* 2007; Randall & Moss 1990; Bleumenthal *et al.* 1991 Borghi *et al.* 1997). Studies, however, that analysed grain protein content as a function of tillage system reported no significant differences (Baenzinger *et al.* 1985; Bassett *et al.* 1989; Cox & Shelton 1992; Gursoy *et al.* 2010). In contrast, Lopez-Bellido *et al.* (1998); De vita *et al.* (2007) reported higher grain protein content under conventional, compared to non-inversion tillage systems.

1.4.8. Cover crops

Cover crops are often perennial or annual legume plant species introduced into the crop rotations to provide beneficial services to the agroecosystem (Fageria 2009). According to Fageria (2009); Hartwig & Ammon (2002); Teasdale (1996) intercrops, bi-crops, catch crops, green manure crops and living mulches can be synonymous with cover crops (Table 1.1) based on their intended main functions. The usage varies: fixation of nitrogen (Jones 1992; Jones & Clements 1993), conserving water and nutrients (Hartwig & Ammon 2002), protecting soil from erosion (Langdale *et al.* 1991), controlling weeds, pests and diseases (Teasdale 1996; Trenbath 1993), and improving soil physical, chemical and biological properties (Duda *et al*. 2003).

Cover crops in combination with reduced tillage techniques reportedly increase nutrient-use efficiency by reducing losses from leaching, volatilization, and erosion (Tilman *et al.* 2002). Diversifying cropping systems also allows growers to better adapt to climatic extremes and a wide range of environmental realities, and to choose more sustainable options as reported by Liebig *et al.* (2007). Diversified cropping systems, however, are more difficult to manage than conventional systems and the success of crops may vary based on location or specific environmental conditions (Cavigelli *et al.* 2009; Taylor *et al.* 2001). Berkvist *et al.* (2011) reported that growers hesitate to adopt diversified cropping systems because cover crops are not high enough to warrant mineral fertilisers or synthetic chemicals in terms of nitrogen input or weed suppression. Nevertheless, dynamic crop rotations should be able to balance crops that deplete soil fertility and organic matter such as cereal grains, with crops that possibly restore soil quality such as legumes (Hanson *et al.* 2007; Taylor *et al.* 2001).

Table 1.1 Terms used in context to highlight intended function

Cover crop	Covers soil when cash crop are spatially or temporally unable to do so. Decrease soil erosion and improves soil structure and fertility
Catch crop	Often used to describe a crop that absorbs mineral N from the soil and prevents leaching losses to the environment.
Green manures	Mainly legumes grown to improve the N supply for successive crops. Typically grown for a specified period during a rotation and then ploughed into the soil before the succeeding crop is established
Intercropping	Simultaneous growing of two or more crop species in the same field, to improve the use of resources when all components are producing yield for harvest
Undersowing	A cover crop grown with a main crop that continues its growth after harvest of the main crop (also called relay cropping)
Living mulches	A cover crop that are planted either before or after main crop and maintained as living ground cover throughout the growing season (often referred as intercropping).

1.4.8.1. Undersowing

Intercropping in the UK occurs normally in the form of undersowing (Hartl 1989). Perennial legumes can be undersown either with winter or spring sown cereal in spring without severely reducing the yield of the main crop, and allowing the development of subsequent ley after harvest of main crop (Wallgren & Linden 1994; Abdin *et al.* 1997). Legumes supply a renewable source of nitrogen through biological nitrogen fixation, thus providing an economically and ecologically appropriate means of delivering nitrogen to non-leguminous crops whilst, reducing off-farm nitrogen inputs (Kirkegaard *et al.* 2008; Thiessen Martens *et al.* 2001). Nitrogen derived from biological fixation can accumulate in the tops, crowns, roots, or nodules of the legume plant species, but the amount and main location where plant partition N varies with legume species (Badaruddin & Meyer 1990). As a result, nitrogen contribution by legumes may vary, depending on where they assimilate nitrogen in their biomass and how they are managed.

The effectiveness of undersown cover crop to provide other benefits in terms of weed suppression, pest and disease control also varies with the type of legume species grown, time of sowing, biomass production, harvest management, and other environmental factors (Hartwig & Ammon 2002; Badaruddin & Meyer 1989). The fundamental goal of undersowing is to avoid bare soil between cash crop plantings; this not only protects soil, but captures sunlight and produces biomass that enhances soil quality (Hartwig & Ammon 2002). Numerous other benefits can accrue through this approach, such as reduced compaction (Bristow & Horton 1996); minimising the number of cultivations required, thereby reducing soil structure deterioration (Teasdale & Mohler 1993). Intercropping can also potentially improve soil physical structure by adding organic matter to the soil (Duda *et al.* 2003), suppressing weeds (Liebman & Dyck 1993), and by reducing the incidence of pests and diseases (Teasdale 1996; Hiltbrunner *et al.* 2002). However, an undersown crop may be competitive with the main crop for water and nutrients which can possibly reduce main crop growth and yield (Clements & Williams 1967). Nevertheless, competitiveness of legume undersown with cash crop can be reduced. This can be done by lowering the seed rate of the undersown crop or by delaying the undersowing in relation to the sowing of the cash crop or by increasing the seed rate of the cash crop and by using suitable species of combination (Charles 1958).

1.4.8.1.1 Competition and yield advantages in undersowing

Intercropping systems are more complex in comparison to monoculture systems. Plant to plant interactions will occur during the growth process, especially when the component species are exploiting growth resources from the same location or at the same time (Vandermeer 1989; Ong *et al.* 1996). Thus, in crop mixtures, any species utilising the same combination of resources will be in direct competition (Willey 1979). Nevertheless, main crop can possibly have an advantage due to the components of the intercropping differing in their resource use, thereby better complementing each other (Willey 1979).

Pot studies in the 1930's showed that legumes could excrete nitrogen during growth and so benefit an associated non-legume (Nicol 1935; Virtanen *et al.* 1937; Wilson & Burton 1938). When considering the benefits a cereal may derive from growing with a legume it is important to consider (I) The time at which the cereal is capable of taking up nitrogen and (II) the time at which the companion legume releases it (Charles 1958).

The time of sowing of the understorey crop could cause potential yield differences between the cereal and the understorey crop. Charles (1958) reported no reduction in cereal yield when the understorey crop was sown at the time when cereal was well established, but yield reduction occurred when both crops were sown at the same time. Yield reduction may occur due to undersown crops competing for light, water, or nutrients (Brandt *et al.* 1989). Other studies have also reported a cereal yield advantage of undersowing a cover crop due in part of effective weed suppression by vigorous growing cover crop, without affecting the primary crop (Hauggaard-Nielsen *et al.* 2008; Blackshaw *et al.* 2001b; Brennan & Smith 2005; Ross *et al.* 2001).

1.4.8.1.2 Undersowing effects on grain protein content

The performances of organic cereal-legume intercrops are highly variable in terms of grain protein content (Berry *et al.* 2002; Bond & Grundy 2001; Jones & Clements 1993). Jensen (1996) reported that intercropped cereal produce higher grain protein content when compared to sole crops. These advantages are assumed to be linked to the complementary use, in time and space, of resources by the intercropped species (Jensen 1996). Similar results of intercropping on higher grain protein have also been reported by Hauggaard-Nielsen *et al.* (2001); Corre-Hellou *et al.* (2006); Lauk & Lauk (2008). According to Gooding *et al.* (2007), the effect of intercropping on the grain protein content of cereals is a result of (I.) the low competitiveness of legumes for soil mineral nitrogen, compared to the cereals and (II.) the competition for light between the species, limiting the intercropped cereal biomass compared to sole crops.

1.4.9 Cereal-legume bi-cropping

Legume swards normally have to be ploughed and immediately followed by an arable crop to utilise legume nitrogen from the soil. Nevertheless, the complete incorporation by mechanical means can potentially reduce its competitive ability in continuous cereal cropping situation (Grubinger & Minotti 1990; Thorsted *et al.* 2002). The development of drills capable of introducing seed into undisturbed soil made it possible to sow a non-leguminous species in an established legume sward (Clement & Williams 1967). Initially a sward of white clover needs to be established and then the clover should be defoliated by mechanical means and cereal is then drilled into existing white clover

(Clements & Donaldson 1997). In such a system the non-legume might benefit from both residual and subsequent nitrogen fixation (Jones 1992). Survival of the legume understorey would lead to the process being repeated with a succession of crops (Jones 1992). The continuous presence of a crop should minimise the loss of nitrogen through leaching because the roots of cereal and legume absorb any mineralised nitrogen. Although, many studies have reported that the fixed nitrogen is available for both current and subsequent cereal crops (Fujita *et al.* 1992; Pappa *et al.* 2006), other studies have not observed nitrogen transfer from legume to cereal in current year (Oforoi & Stern 1987).

Many previous studies have demonstrated the potential to incorporate the benefits of legume cover crops into continuous annual grain cropping systems without sacrificing a year of grain production (Thiessen Martens *et al.* 2005; Walker *et al.* 2011). However, including more than one crop in a cropping system can also have negative impact on crop yield and quality (Pridham & Enz 2008). Pridham & Enz (2008) reported that cereal-legume intercropping often produce inconsistent grain yield and more weeds than in monoculture systems. Lithourgidis *et al.* (2011) and Williams & Hayes (1991) observed lower growth and dry matter yields of cereal in cereal-legume intercropping than monoculture, in which they attribute to increased competition from a legume intercrop. Jones & Clements (1993) found spring wheat was unable to compete with the legumes species, but winter wheat survived although yielding poorly. In general, although competition is a concern, many authors demonstrated increased resource use efficiency, reduction of pests and weeds in intercropped systems when compared to sole cropping systems (Hauggard-Nielsen *et al.* 2008; Thiessen Martens *et al.* 2005; Walker *et al.* 2011). In addition, the land equivalent ratio or relative land area required for monocrops to produce the same yield as intercrops is often greater for both crops in an intercropping systems compared to the same crops grown in monocultures (Lithourgidis *et al.* 2011; Reynolds *et al.* 1994). Thus, establishing cereals successfully and maintaining the desired balance of components to ensure reasonable cereal yield and legume survival is a skilful operation (Clements *et al.* 1994b).

1.5 Need for research on organic wheat production – UK perspective

A number of severe recent food scandals worldwide have led to an increasing awareness among consumers on improving health and environment (Rotner-Schobesberger *et al.* 2008; Niessen & Hamm 2006). Besides this, shoppers appreciate the principles and practices involved in organic food production for transparency and consumer orientation. Accordingly, the consumption of organic food has been increasing globally and the organic food sector is experiencing a strong and constant growth in Europe and North America (Willer & Kilcher 2012). Recent sales in the UK, however, have been less buoyant.

In the UK, wheat is the most important cereal crop with an annual harvest of more than 15 million tonnes (Living Countryside 2011). The organic wheat production area in the UK continues to be variable, and hence sometimes unable to consistently provide flour of suitable quantity (and quality) to meet the demands of the organic sector (Mader *et al.* 2002). As a result, more than 50% of the requirement for organic bread-making wheat and 80% of feed wheat is being imported (Mader *et al.* 2007), which indicate the potential for research that needs to address the challenges for the expansion of the UK organic wheat sector. This can be possibly achieved by identifying and better managing the effect of various agronomic practices on the yield and protein content of organic wheat. Improving technical and scientific knowledge about the challenges involved on organic wheat production will therefore help organic growers and researchers to possibly identify and/or develop better fitting agronomic strategies with a lower environmental impact, and also identify the added-value of typical and niche conservation agricultural practices.

1.5.1 Study aim and objectives

Driven by the conclusions drawn from a review of literature and the importance acknowledged for need for more research in UK organic wheat production, the main aim of this research study was to investigate suitable husbandry practices including different cultivation techniques and legume undersowing for organic wheat production. These investigations will address the potential interactions among various farm management practices including:

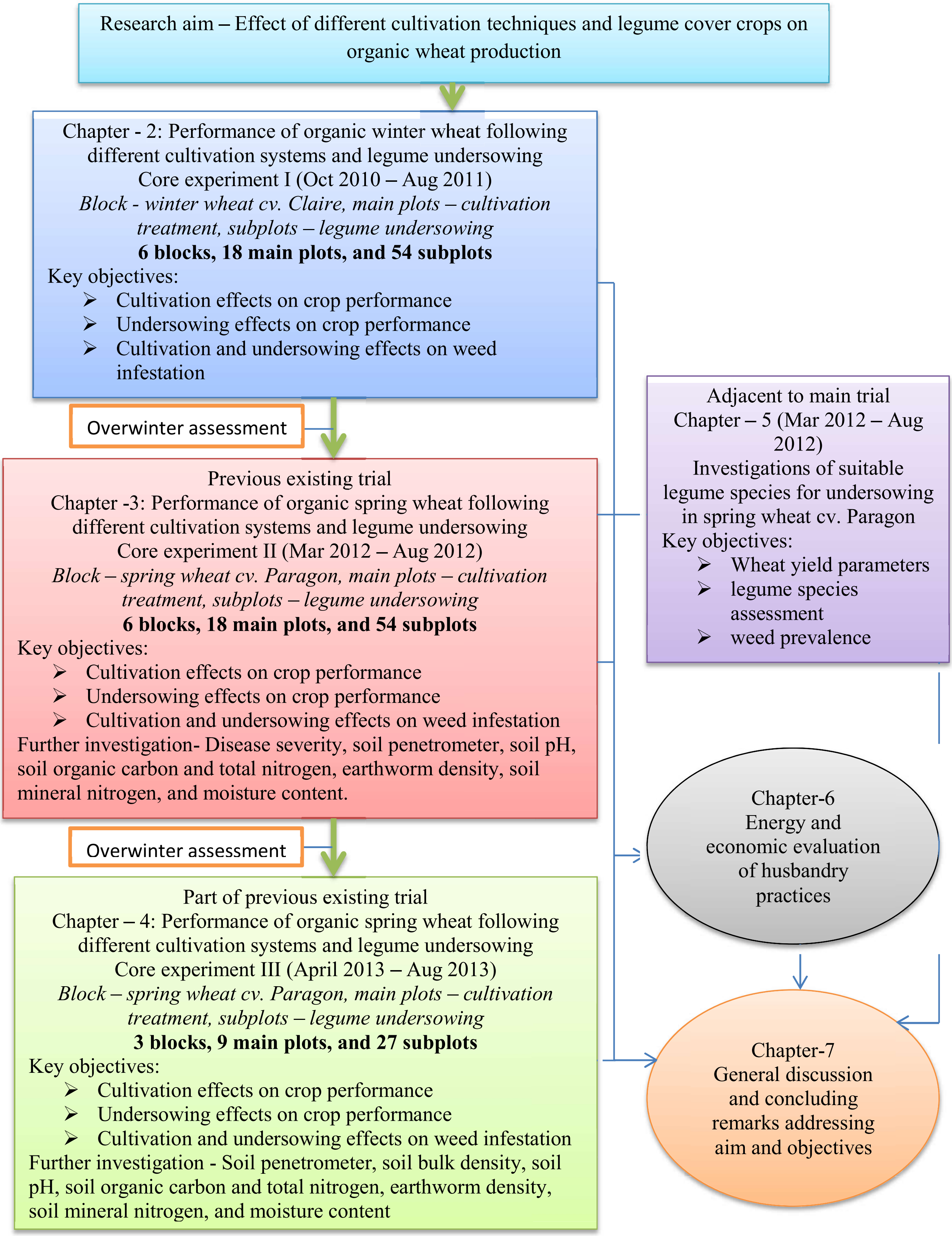
- Investigation of different cultivation techniques (conventional tillage or non-inversion tillage involving high residue non-inversion tillage and low residue non-inversion tillage) for reliable crop production and productivity.
- Assessing the suitability of either undersowing white clover or black medic, compared with non-undersowing on crop field and yield performance.
- The efficacy of cultivation techniques and legume undersowing on weed infestation.

Although, many recent research projects (by ADAS, Teagasc, NIAB and HGCA) in the UK have attempted to assess the use of legume cover crops in reduced tillage settings, the management of such systems were reported to be difficult and complex, and the success of this type of system has often varied, based on location or specific environmental conditions. Hence continued research seems justified to identify the key challenges and promising outcomes in relation to crop type, cropping pattern, site location, specific weather events, and soil type. Local specificity plays an important role in determining the performance of an agricultural management practices (Smolik *et al.* 1995). Tiziano *et al.* (2011) reported that local characteristics deserve attention as agricultural practices should not be adopted blindly, but with much concern for specific local features. What may be a fitting agronomic strategy for a given area may not be practicable with the same results, in another (Smolik *et al.* 1995). Therefore, adaptive agronomic practices have to be performed to understand and acquire knowledge about complex interaction of husbandry systems and their associated agro-ecosystem resilience.

1.5.2. Research approach

The main goal is to investigate the effects of different cultivation techniques and legume undersowing on organic wheat. However, as the study progressed, various other parameters (Figure 1.1) were also included/explored for wider understanding of overall causes and benefits of adopting various organic husbandry practices.

Figure 1.1 Progression of the research study



Chapter - 2

CORE EXPERIMENT – I: PERFORMANCE OF ORGANIC WINTER WHEAT FOLLOWING DIFFERENT CULTIVATION SYSTEMS AND LEGUME UNDERSOWING

2.1. Introduction to 2010/11 core experiment

Organic farming systems generally depend on mouldboard ploughing for seedbed preparation, and to deal with weeds (Cannell 1985). Seedbed condition is crucial in determining the most suitable conditions for crop growth (Atkinson *et al.* 2007). Cultivation prepares soil for seeding by assisting the decomposition of organic matter, aeration of the soil, weed control, and most importantly seedbed preparation (Carter *et al.* 2003a). Whether cultivation of the soil improves its condition for seed germination, establishment and yield has been questioned, and in many cases, it has been shown that excess cultivation can have detrimental effects on soil environment and therefore leading to poor crop productivity (Ball *et al.* 1994; Scott *et al.* 2005; Unger 1979).

Recent pressure on farm incomes and concerns over negative soil and environmental impacts has led to alternative tillage systems called non-inversion tillage. In turn, non-inversion tillage involves shallow or deeper working depths, without soil inversion, whereby crop residues are mixed into the topsoil, but leave a proportion on the soil surface after seed placement (Cannell 1985; Davies & Finney 2002). In the process, the system minimise the costs associated with cultivation; improves the timeliness of cultivation and also reduce soil erosion (Sprague & Triplett 1986; Vakali *et al.* 2011). However, most organic growers hesitate to adopt non-inversion tillage systems because of inconsistent yields and protein content due in part to nitrogen deficiency and weed competition (Vakali *et al*. 2011; Bond & Grundy 2001).

Weed management is a focal issue in organic farming (Barberi 2002), where weeds are controlled by direct destruction (manual or mechanical), preventive measures (tillage or crop rotation) and by enhancing crop tolerance of weeds (choice of genotypes or sowing method) (Anderson 2010). Mechanical weed control is often practiced in organic farming, but concerns over negative impacts due to energy consumption and additional traffic on field have led to alternate search for weed managements (Hatcher & Melander 2003). Crop diversification helps to stabilize agricultural crops and weeds, and this changes the composition of weeds species (Buhler 2003). Agricultural crops with different growth cycles (winter or spring) provide unfavourable conditions for weed growth (Davies & Welsh 2002). This prevents weed spread, germination, and seed ripening (Koocheki *et al.* 2009). An important role has been given previously to the search for alternate crop production strategies - including catch crops, intercrops, bi-cropping (Liebman & Gallandt 1997; Liebman & Davies 2009), and crop potential usage for suppressing and tolerating weeds (Davies & Welsh 2002). Growing two or more crops together is a common practice in developing agricultural systems (Liebman & Davies 2009). Cereal-legume bi-cropping not only provides nutritional benefits but also greater competitiveness against weeds (Amosse *et al.* 2013; Blaser *et al.* 2011); reduced susceptibility to pest and diseases (Scholberg *et al.* 2010); increased biological activity (Hartwig & Ammon 2002); enrichment of soil organic matter (Jokela *et al.* 2009) and also potentially a reduction of growing costs (Jones 1992; Jensen 1996).

Intercropping in the UK usually takes the form of undersowing (Hartl 1989). Undersowing legume cover crops at spring in an established winter wheat means that the cover crop could be well established after wheat harvest (Thiessen-Martens *et al.* 2001). In this context, legume cover crop inserted between the cash crop aids in maintaining ground cover that would otherwise be occupied by weeds, whilst maintaining a cash crop every year through the sequencing of winter and spring crops (Thiessen-Martens *et al.* 2001). Accordingly, this method is also expected to limit competition between primary crop and cover crop in comparison to simultaneous cereal-legume intercropping (Blackshaw *et al.* 2010). Nevertheless, adopting this techniques under reduced tillage settings often results in lower crop yields (Carof *et al.* 2007; Hiltbrunner *et al.* 2007a). Previous studies have demonstrated weed control advantages over sole crops by utilising resources from weeds and suppressing weed growth (Blackshaw *et al.* 2010; Liebman & Davies 2009). However, the efficacy of a cover crop on weed suppression mainly depends on its establishment ability and biomass production (Liebman & Davies 2009).

To understand the effect of these external factors such as cultivation techniques and legume undersowing, knowledge about growth and development of the wheat crop is crucial. Plant establishment, tillering, and yield forming shoots are determined during the foundation growth stages of wheat. The construction stages are comprised of spikelet initiation, floret initiation, active spike and stem growth, anthesis and pollination as well as floret senescence. The final stage is grain set and grain filling (HGCA 2008). The final crop yield is the result of various yield components, therefore, that individually and in combination contribute to grain production (HGCA 2008). Until recently, use of non-inversion tillage and legume undersowing has been developed more successfully for conventional crop production. Transforming these practices to organic farming is a major challenge. A field experiment was therefore set up in each of three years, using winter or spring wheat as bioassay crop to investigate their performance following contrasting cultivation methods included full inversion tillage (CT) against non-inversion tillage involving low residue non-inversion tillage (LRNiT) and high residue non-inversion tillage (HRNiT) and also undersowing either white clover (WC) or black medic (BM) or no undersowing (N_{us}). Organic wheat performance, on the basis of establishment, growth assessments, weeds infestation, and grain yield was assessed to determine the influence of the various husbandry techniques.

2.2. Materials and Methods for 2010/11 experiment

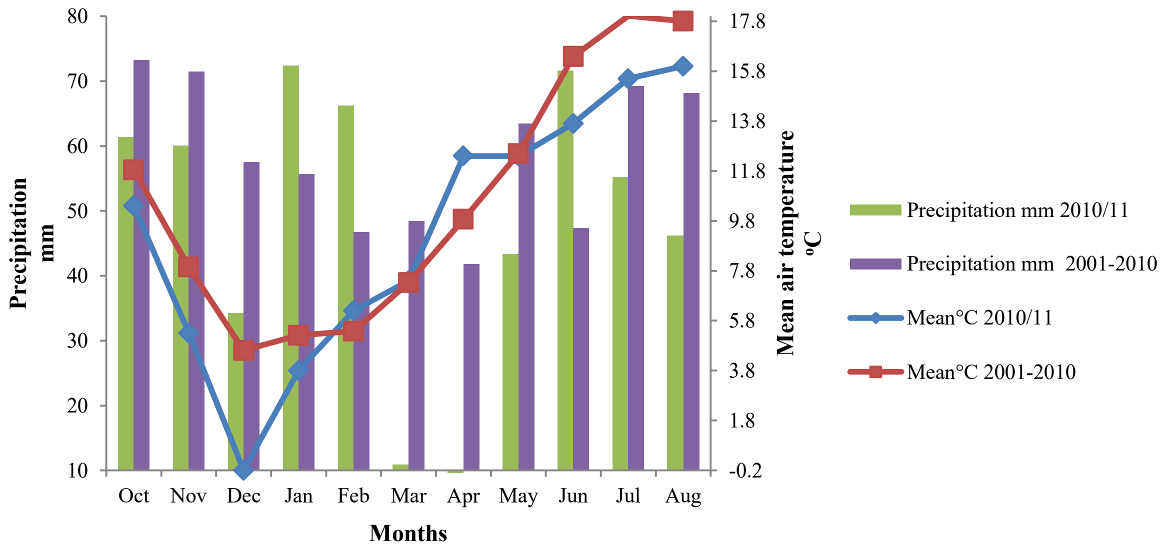
2.2.1 Site details

After two years of perennial ryegrass/white clover ley, a field experiment was conducted from October 2010 to August 2011 on Evesham soil series on land registered with the Soil Association for organic production at the Royal Agricultural University's Harnhill Manor Farm (NGR SP 075 006) near Cirencester, UK situated at 51^{o} 42'N latitude, 01^{o} 59' W longitude at an altitude of 135m above sea level. The soil texture, determined by mechanical analysis, was clay (22% sand, 40% clay, and 38% silt) and PH of 7.8. Soil phosphorus content was 14.0mg l^{-1} or Index 1 while, the potassium was 208.0mg l^{-1} or Index 2. Index values rated according to DEFRA (2010).

2.2.2 Meteorological conditions

The 2010/11 winter wheat growing period recorded an average air temperature of 9.4°C and a precipitation of 531.2mm. Minimum and maximum air temperature was read in the month December (-0.2°C) and August (16°C). Maximum and minimum precipitation received was in the month January (72.4mm) and April (3.3mm). The winter wheat cropping period experienced dry spring and moderately lower precipitation, compared to long-term seasonal average (Figure 2.1).

Figure 2.1 Mean air temperature and amount of precipitation during 2010/11 crop season. Royal Agricultural University Meteorological station, (NGR SP 42 004 011)



2.2.3 Experimental design and treatment structure

The experiment was arranged in a randomized complete block design with three cultivation treatments replicated in six separate blocks. The selected field of 5.4ha was divided into six separate blocks of 90 x 100m. Each block was divided into three cultivation treatment portions of 30 x 100m and assigned as main plots.

Land preparation techniques commenced on 1 November 2010. One portion was ploughed (CT) using a five furrow Kverneland reversible plough to a working depth of 20cm and pressed. Secondary tillage synchronous with drilling was with a Kuhn power harrow combination seed drill to a working depth of 8cm. The second portion received low residue non-inversion tillage (LRNiT) involving two pass tillage operations using

Simba ST bar fitted ahead of mounted Simba X-press, to a working depth of 25cm and 12cm. Secondary tillage synchronous with drilling was with a Vaderstad Rapid-A system disc in combination with seed drill to a working depth of 8cm. The third portion was high residue non-inversion tillage (HRNiT), involving one pass tillage operation using Simba ST bar fitted ahead of mounted Simba X-press, to a working depth of 25cm and 12cm followed by heavy planter Eco-dyn integrated seed drill to a working depth of 26cm. The amount of surface soil cover varied depending on whether the soil cover were completely dispersed by plough + drill (CT) or mixed using two pass tillage operations + drill (LRNiT) or mixed using one pass tillage operation + drill (HRNiT). The percentage of cover on or near the soil surface after drilling was typically assumed as CT 0%, LRNiT 30% and HRNiT >50% (Plate 1a). This characterised the main plot treatments. The details of cultivation treatments have been previously reported by Vijaya Bhaskar *et al.* (2013a, b).

Plate 1a. Seedbed conditions after contrasting cultivation treatments

For the cropping year 2010/11, winter wheat cv. Claire at 410 seeds m^{-2} was planted on 5 November 2010. On 14 April 2011, the main plot treatments (30 x 100m) was split into three subplots of 30 x 33.3m and undersown (broadcasting by hand) either with white clover (WC) (*Trifolium repens* cv. Nemuniai*;* 7kg ha^{-1}) or black medic (BM) (*Medicago lupulina* cv.Virgo Pajbjerg*;* 8kg ha^{-1}) into the established wheat stand or not undersown (N_{us}). The trial was harvested on 25 August 2011. The treatment structure (Figure 2.2 and Plate 1b) was a full factorial of:

Winter wheat (block) ***x*** *tillage systems (main plot)* ***x*** *+/- undersowing (subplot)*

Figure 2.2 Trial design for organic winter wheat 2010/11

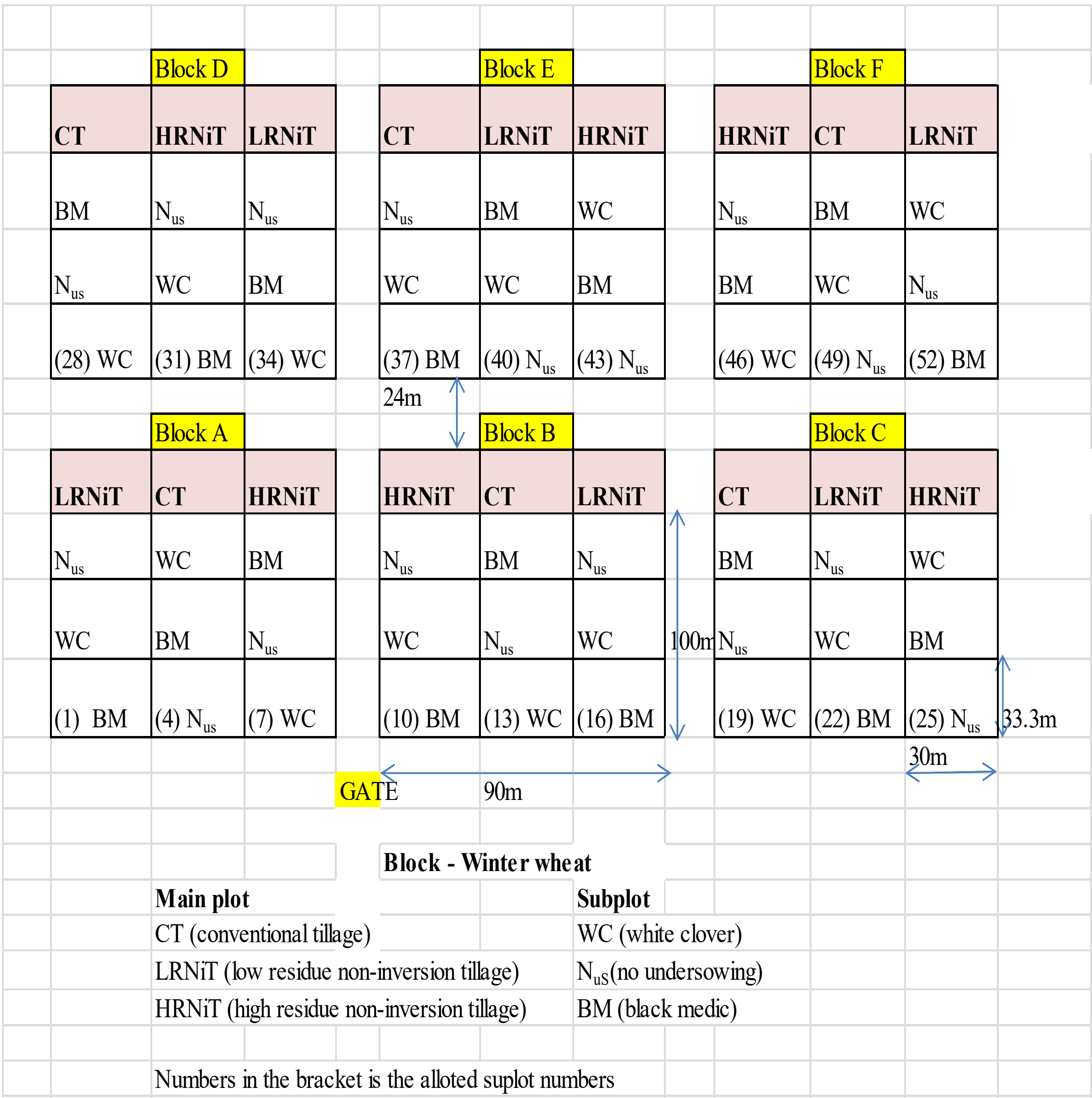
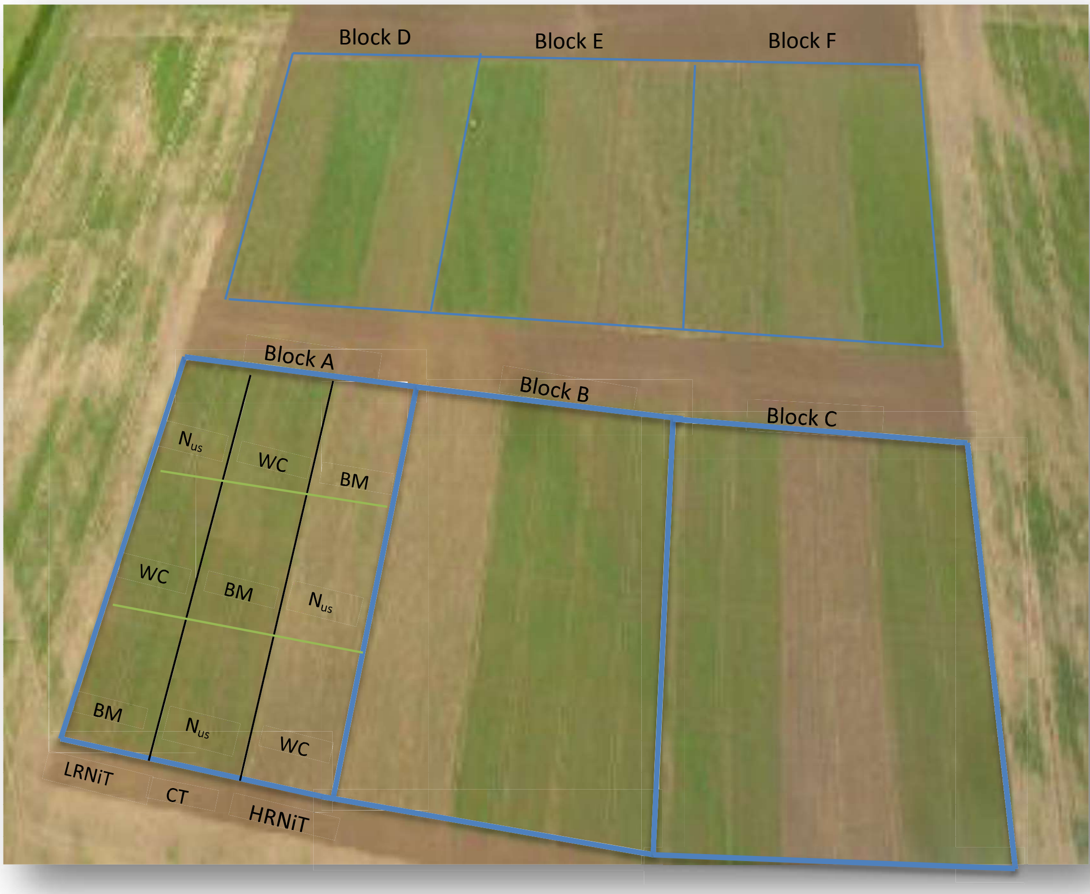


Plate 1b. Full trial after cultivation and undersowing treatments



Varietal choice

Organic winter wheat is likely to be the first crop grown after the fertility-building phase in the rotation (Lampkin *et al.* 2002). Previous studies that preferred organic bread-making winter wheat as their first crop choice reported that the grain protein levels were low, with variable grain yield (Thompson *et al.* 1993a; Starling & Richards 1990). Hence, for this experiment Group 3 (biscuit/cake-making) – semi-dwarf winter wheat cv. Claire was preferred, which would be expected to yield more than bread-making winter wheat variety, and still possibly attract an organic price premium (NABIM 2013; Thompson *et al.* 1993a). Additionally, Claire wide drilling window, prostrate habit of emergence, highly resistant to lodging, unrivalled disease resistance and reliable performance of yield under untreated trials has made it favourable for organic growers to be the first crop choice (NABIM 2013).

Sowing date

In the UK, autumn sowing dominates because of greater potential crop yields than a spring sown alternative (Hayward 1990). The time of drilling is important in winter wheat to avoid problems of autumn germinating weeds (Wijnands 1990). Delayed-sowing in organic farming is reportedly practiced, as it avoids heavy weed infestations (Jordan *et al.* 1990). Previous organic research at Harnhill has also shown that weeds competition can be greatly reduced in winter wheat by delayed sowing (Gooding *et al.* 1998). For the present study, winter wheat cv. Claire was therefore, sown in mid-November.

Seeding rate

The seeding rate (the number or weight of seeds drilled per metre square) are determined by the field conditions (i.e. soil type) and the time of year (Atkinson 2008). Under organic farming conditions, to establish different cultivation treatments a higher seeding rate (≥400 seeds m^{-2}) is preferred, as germination percentage are presumed neither predictable nor consistent due to the possible variation in seedbed conditions associated with contrasting husbandry techniques, later drilling dates, lack of seed dressing and slug control. Seeding rate is known to influence grain yield, and previous studies has demonstrated higher seeding rate in wheat as one of the means of obtaining higher grain yield (Lampkin *et al.* 2011; Tompkins *et al.* 1991; Hiltbrunner *et al.* 2007b). However, increased seed rates can lead to greater competition between plants; thereby possibly influencing the establishment percentage (Spink *et al.* 2000). Despite plant competition, higher seed rates can be used to achieve high plant densities that can increase the ground cover and potentially reduce the biomass of most weed species (Richard 1989). Nevertheless, differences in cultivation techniques, seedbed conditions, and weed pressure can determine the outcome of crop-weed competition (Olsen *et al.* 2005; Samuel & Guest 1990; Blackshaw 1993; Murphy *et al.* 1996).

Drilling depth

Drilling depth can be difficult to control and is dependent on the performance of contrasting pre-sowing cultivation techniques on seedbed preparation. If the seedbed is poorly consolidated this can lead to deep sowing, if too dense then the seeds may not be adequately covered (which may result in loss due to pest damage) (Atkinson 2008). Furthermore, the presence of surface soil cover (crop residues) under non-inversion tillage systems may interfere with drill, and thereby causing uneven sowing depth and seeding row space (Siemens *et al.* 2004). In general, drilling aims to be deep enough to ensure good coverage and quick emergence (Atkinson 2008). Recommended sowing depth for wheat varies from 2 to 4cm depending upon the soil type and soil conditions (HGCA 2008). For the experiment 2010/11, uniform planting depth of 2cm and coulter row spacing of 12.5cm was used for all combination seed drills. Although, uniform planting depth and row spacing was maintained, drills may perform differently based on pre-sowing cultivation.

2.2.4 Assessments

Approximate wheat growth stages were considered (with the use of key Tottman & Broad 1987) for conducting assessments as listed in Table 2.1.

Table 2.1 Assessments conducted at different wheat growth stages

Assessments	Approximate growth stages
Number of plants established, tillers and total number of shoots	On/or before GS30
Total number of shoots	On/or after GS31
Weed numbers	On/or before GS30 and on/or after GS31
Growth assessments (plant biomass)	On/or before GS31, on/or after GS39 and on/or after GS61
Wheat plant heights	On/or after GS71 and on/or before GS87
Wheat ear numbers	On/or after GS71 and on/or after GS87
Disease incidence	On/or after GS71
Final harvest	On/or after GS87

Wheat establishment was determined by counting the number of plants using a 0.25m^2 quadrat randomly placed with ten replications per subplot at 05 February 2011.

The number of wheat tillers was assessed using a $0.25m^2$ quadrat randomly placed with ten replications per subplot at 02 March 2011.

The total number of wheat shoots (main stem and tillers) was assessed using a $0.25m^2$ quadrat randomly placed with ten replications per subplot at 29 March 2011 and 18 April 2011.

Initial weed density was assessed twice using a $0.25m^2$ quadrat randomly placed with ten replications per subplot at 25 March 2011 and 20 April 2011.

Growth assessments were evaluated by hand harvesting from each subplot using a $0.25m^2$ quadrat randomly placed with five replications at 08 April 2011 (Phase I), 20 May 2011 (Phase II) and 18 June 2011 (Phase III). All the samples were separated as wheat, legumes (specifically white clover or black medic), and total weeds (specifically broadleaf or grass weeds only at Phase II and III). The biomass or dry matter (DM) was determined after drying at 105°C overnight. For undersowing treatments, in particular, non-undersown (N_{us}) was not completely free of legumes due to the natural regeneration of the previous ley; hence legumes were separated from other broadleaf weeds, even though they were legume weeds rather than undersown legumes.

Wheat plant heights were initially measured using metre rule, but later plant heights were assessed using rising disk apparatus which comprised of a rectangle cut from expanded polystyrene weighing 50g and measuring 30 x 50cm. A hole was centrally bored measuring 4cm in 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. Twenty random measures per subplot were taken at 10 July 2011 and 05 August 2011.

The number of wheat ears was assessed using a $0.25m^2$ quadrat randomly placed with ten replications per subplot at 20 July 2011 and 10 August 2011.

The disease incidence of leaf blotch (*Mycosphaerella graminicola)* was visually assessed with the use of a key Anon (1979) at 02 July 2011. Twenty wheat shoots were sampled at ten random points per subplot, and top three leaves (leaf 1 (flag leaf), leaf 2 and leaf 3) were monitored for disease severity.

Before final biological harvest, wild oat (*Avena fatua*) were removed from each subplot manually (15 August to 21 August 2011), and the numbers were recorded.

Final Biological harvest: The trial was hand harvested on 25 August 2011 by using a $0.25m^2$ quadrat randomly placed with five replications per subplot. Each sample was separated into wheat ears, straw, legumes (black medic or white clover) and total weeds (broadleaf and grass). All the samples were dried at 105^oC overnight and DM was recorded. Ears were then threshed by hand and the amount of grain was weighed to obtain total grain weights, and therefore grain yield. The thousand grain weights (TGW) of the dried sample were recorded after using an automatic feeder and counter (Farm-Tec, Scunthorpe). All the samples were milled into a fine powder (Cyclotec 1093 Sample Mill) and nitrogen concentration (N %) of 25mg (± 0.05mg) was analysed by Elementar Cube auto analyser (Elementar Analysensysteme GmbH). Harvest index was calculated by the ratio of grain weights to the total above ground biomass (Donald & Hamblin 1976). Grain protein content was calculated by multiplying grain N % with 5.7 (Osborne 1907). Total grain N uptake, total wheat N uptake (calculated by adding total grain N uptake and total straw N uptake), total legume and weeds N uptake and finally, nitrogen harvest index were calculated using the following formula (Moll *et al.* 1982; Fageria *et al.* 2008).

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

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

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

2.2.5 Data analysis

Statistical analysis were performed on all the data collected using the split plot analysis of variance (ANOVA) model in Genstat (15th Edition VSN International Ltd, Hemel Hempstead, UK) to establish differences between different cultivation, undersowing and their interactions. All the data's were checked for uniformity of residuals across the range before reporting results. The results of ANOVA (Clewer & Scarisbrick 2001) are reported quoting treatment means, residual degrees of freedom (df), standard error of a difference (SED) or Fisher's Protected Least Significant Difference (LSD) and the *p*-value (significance level of $p < 0.05$).

Disease data for *M. graminicola* (area of disease in percentage scored) was logit transformed to reduce heterogeneity of variance using the formula: In[X / (100-X)] where X= area of disease (%). On any analysed variables, if there was no statistical difference (^{ns} non-significant, $p > 0.05$) either of tillage or undersowing treatments, then just the grand mean of main plot treatments, were reported in the results. The N % from the dry matter of all the plant samples (wheat, legume species and weeds) that was analysed using elemental analyser is only reported when significant differences was observed between tillage or undersowing treatments unless, estimated total crop N uptake (kg ha^{-1}) was reported.

2.3 Results for 2010/11 core experiment

Wheat establishment, tiller numbers, and total number of shoots

Among three cultivation treatments (Table 2.2), conventional tillage (CT) had significantly higher plant establishment followed by low residue non-inversion tillage (LRNiT), compared with high residue non-inversion tillage (HRNiT). Cultivation treatments that affected wheat establishment also influenced tiller numbers with CT having significantly higher number of tillers than LRNiT or HRNiT. Total number of wheat shoots at both assessments showed a similar trend. Implying that the cultivation treatments that gave greatest wheat establishment and tiller numbers had no effect on total number of shoots, with CT and LRNiT having significantly higher number of total shoots than HRNiT. The mean values were therefore, reported in the results (Table 2.2)

Table 2.2 Wheat field performance under three tillage treatments (2010/11)

	Establishment (counts m^{-2})	Tiller (numbers m^{-2})	Total shoot (numbers m^{-2}) (*mean values*)
CT	285a	588a	799a
LRNiT	241b	498b	755a
HRNiT	197c	369c	560b
SED (10 df)	19.05*	31.9*	54.0*

*Values followed by the same letter do not differ significantly (*p <0.05)*

Weeds population density

At both assessments, total number of weeds was significantly higher with HRNiT followed by LRNiT, compared with CT (Table 2.3). The trend observed from these results indicated that as the level of tillage intensity decreased, the weed density tend to increase.

Table 2.3 Weed numbers under three tillage treatments (2010/11)

	Weed (numbers m^{-2}) (25 March 2011)	Weed (numbers m^{-2}) (20 April 2011)
CT	16c	103c
LRNiT	47b	161b
HRNiT	118a	295a
SED (10 df)	10.35*	20.22*

*Values followed by the same letter do not differ significantly (*p <0.05)*

Wheat biomass

At Phase I, CT had significantly higher wheat DM than LRNiT or HRNiT (Table 2.4). However, at Phase II and III, CT and LRNiT had significantly higher wheat DM than HRNiT. Throughout the assessments, there were no statistically significant effects of undersowing or tillage x undersowing interaction on wheat DM.

Table 2.4 Wheat biomass under three tillage treatments (2010/11)

	Wheat DM (t ha^{-1}) Phase I	Wheat DM (t ha^{-1}) Phase II	Wheat DM (t ha^{-1}) Phase III
CT	1.90a	5.29a	10.00a
LRNiT	1.32b	4.79a	9.84a
HRNiT	1.11b	3.66b	8.22b
SED (10 df)	0.140*	0.474*	0.624*

*Values followed by the same letter do not differ significantly (*p <0.05)*

Total weeds biomass

At both assessments, total weeds DM were significantly higher with HRNiT than LRNiT or CT (Table 2.5). Throughout the assessments, there were no statistically significant effects of undersowing or tillage x undersowing interaction on weeds DM.

Table 2.5 Weeds biomass under three tillage treatments (2010/11)

	Weeds DM (t ha^{-1}) Phase II	Weeds DM (t ha^{-1}) Phase III
CT	0.051b	0.135b
LRNiT	0.080b	0.237b
HRNiT	0.210a	0.836a
SED (10 df)	0.049*	0.217*

*Values followed by the same letter do not differ significantly (*p <0.05)*

Weed species composition

Irrespective of cultivation or undersowing treatments, broadleaf weeds identified were *Matricaria recutita* (scented mayweed), *Tripleurospermum inodorum* (scentless mayweed), *Lamium purpurem* (red dead nettle), *Veronica hederifolia* (ivy leaved speedwell), *Galium aparine* (cleavers), *Stellaria media* (chickweed), *Sinapis arvenis* (charlock), *Sonchus arvensis* (perennial sow-thistle) and *Myosotis arvensis* (field forget-me-not). The grass weeds were *Avena fatua* (wild oat), *Alopecurus myosuriodes* (black grass), *Poa annua* (annual meadow-grass), *Poa trivalis* (rough-stalked meadow-grass), and *Lolium perenne* (perennial rye grass).

Assessment at Phase II (Table 2.6) revealed that there was no statistically significant response of cultivation treatments on broadleaf weeds DM. However, at Phase III, CT had significantly higher broadleaf weeds DM than non-inversion tillage systems. At both assessments (Phase II and III), grass weeds DM were significantly higher with HRNiT than LRNiT or CT. The trend observed from these assessments indicated that as the level of tillage intensity increased the broadleaf weeds tend to increase, while the reverse occurred for grass weeds. At both assessments, there were no statistically significant effects of undersowing or tillage x undersowing interaction on weed species.

Table 2.6 Biomass of weed species under three tillage treatments (2010/11)

	Broadleaf weeds DM (t ha^{-1}) Phase II	Grass weeds DM (t ha^{-1}) Phase II	Broadleaf weeds DM (t ha^{-1}) Phase III	Grass weeds DM (t ha^{-1}) Phase III
CT	0.0182a	0.033b	0.0466a	0.088b
LRNiT	0.0138a	0.066b	0.0269b	0.210b
HRNiT	0.0141a	0.196a	0.0255b	0.810a
SED (10 df)	0.0043^{ns}	0.049*	0.0064*	0.216*

*Values followed by the same letter do not differ significantly (*p <0.05, ^{ns} p >0.05)*

Legume biomass

The growth, establishment, and biomass yield of legumes were highly restricted due to less rainfall. Only at Phase III assessment (Table 2.7), significant cultivation, undersowing and tillage x undersowing effects on legume DM was observed. Among cultivation treatments, HRNiT had significantly higher legume DM followed by LRNiT, compared with CT. Among undersowing treatments, WC had significantly higher legume DM than BM or $N_{us.}$ Among tillage x undersowing interaction, WC undersown HRNiT plots had significantly higher legume DM followed by WC undersown LRNiT plots than the rest.

Table 2.7 Legume biomass under different husbandry treatments (2010/11)

	Legume DM (t ha^{-1}) Phase III
CT	0.034c
LRNiT	0.091b
HRNiT	0.149a
SED (10 df)	0.0238*
BM	0.055b
N_{us}	0.026b
WC	0.193a
SED (30 df)	0.0243*
CT x BM	0.036c
CT x N_{us}	0.027c
CT x WC	0.037c
LRNiT x BM	0.04c
LRNiT x N_{us}	0.03c
LRNiT x WC	0.21b
HRNiT x BM	0.09c
HRNiT x N_{us}	0.027c
HRNiT x WC	0.37a
SED (38.88 df)	0.0419*

*Values followed by the same letter for cultivation, undersowing or their interaction do not differ significantly (*p <0.05)*

***Avena fatua* (wild oat)**

Wild oat was severe and more wide-spread across the trial; hence hand weeding was employed just prior to harvest to prevent the spreading of seeds. However, complete hand weeding of wild oat was not achieved. Wild oat numbers removed showed that HRNiT had significantly higher wild oat numbers than LRNiT or CT (Table 2.8). There was no significant undersowing or tillage x undersowing effects on wild oat numbers.

Table 2.8 Wild oat numbers removed from main treatment plots (2010/11)

	Wild oat (numbers removed)
CT	67b
LRNiT	156b
HRNiT	570a
SED (10 df)	177.7*

*Values followed by the same letter do not differ significantly (*p <0.05)*

Mycosphaerella graminicola

Disease severity (logit transformed) on wheat % leaf 1, % leaf 2, and % leaf 3 resulted in statistically non-significant effect of cultivation or undersowing treatments. Irrespective of tillage or undersowing treatments, disease severity for leaf 1, leaf 2, and leaf 3 (grand mean) were -2.50, -2.42, and -2.15 respectively. The splash of rainfall in late spring and summer, after shortage of precipitation in early and mid-spring, resulted in development of *M. graminicola.* However, they were relatively low levels, and therefore not enough evidence to trigger statistically significant difference between treatments.

Plant heights and ear numbers

At both assessments, CT and LRNiT had significantly taller wheat plants and higher ear numbers than HRNiT. The mean values were therefore, reported (Table 2.9). There was no statistically significant effect of undersowing or tillage x undersowing interaction on plant heights or ear numbers at each time of assessment.

Table 2.9 Plant heights and ear numbers under three tillage treatments (2010/11)

	Plant heights (cm) (*mean values*)	Ear (numbers m^{-2}) (*mean values*)
CT	70.00a	591a
LRNiT	68.67a	554a
HRNiT	65.22b	431b
SED (10 df)	1.49*	54.0*

*Values followed by the same letter do not differ significantly (*p <0.05)*

Final biological harvest

Final biological harvest (Table 2.10) showed that wheat ears and straw DM was significantly higher with CT and LRNiT, compared with HRNiT. Wheat grain yield and 1000 grain weights were significantly greater with CT and LRNiT than HRNiT. There were no statistically significant cultivation treatment effects on estimated harvest index.

Table 2.10 Wheat yield performance under different husbandry treatments (2010/11)

	Ears DM (t ha^{-1})	Straw DM (t ha^{-1})	Grain yield (t ha^{-1})	TGW (g)	Harvest index (%)
CT	8.40a	4.27a	7.00a	43.11a	55.28a
LRNiT	7.95a	4.00a	6.58a	43.85a	55.02a
HRNiT	6.61b	3.19b	5.53b	40.91b	56.46a
SED (10 df)	0.332*	0.185*	0.317*	0.752*	0.68^{ns}
BM	7.36a	3.65a	6.13a	41.96a	55.86a
N_{us}	7.69a	3.84a	6.40a	43.40a	55.58a
WC	7.91a	3.97a	6.58a	42.52a	55.32a
SED (30 df)	0.370^{ns}	0.189^{ns}	0.310^{ns}	0.698^{ns}	0.72^{ns}

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05, ^{ns}p >0.05)*

Among cultivation treatments, there were statistically non-significant tillage effects on grain and straw nitrogen concentration. However, due to the variation in grain yield and straw DM between tillage treatments influenced a statistically significant difference in total grain N uptake and total wheat N uptake (Table 2.11). Total grain N uptake and therefore total wheat N uptake were significantly higher with CT and LRNiT than HRNiT. There were no statistically significant tillage effects on nitrogen harvest index or grain protein content. Throughout the assessment, there was no significant effect of undersowing or tillage x undersowing interaction on wheat yield components or yield.

Table 2.11 Wheat nitrogen yields under different husbandry treatments (2010/11)

	Total grain N uptake (kg ha^{-1})	Total wheat N uptake (kg ha^{-1})	Nitrogen harvest index (%)	Grain protein (%)
CT	110.4a	134.3a	73.95a	8.99a
LRNiT	103.5a	126.0a	73.93a	9.00a
HRNiT	85.4b	104.5b	72.35a	8.80a
SED (10 df)	5.12*	6.22*	1.09 ^{ns}	0.159 ^{ns}
BM	96.2a	116.7a	73.57a	8.92a
N_{us}	99.1a	121.5a	72.93a	8.84a
WC	104.1a	126.5a	73.73a	9.03a
SED (30 df)	4.97 ^{ns}	6.18 ^{ns}	0.814 ^{ns}	0.124 ^{ns}

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05, ^{ns} p >0.05)*

Among cultivation treatments (Table 2.12), legume DM and therefore total legume N uptake were significantly higher with HRNiT followed by LRNiT, compared with CT. Similarly, weeds DM and hence total weeds N uptake was significantly higher with HRNiT than LRNiT or CT. Among undersowing treatments, legume DM and therefore total legume N uptake was significantly higher when WC was undersown than with $N_{us.}$ Throughout the assessment, there was no statistically significant undersowing or tillage x undersowing effects on weeds DM.

Table 2.12 Legume and weeds biomass and their nitrogen yields under different husbandry treatments (2010/11)

	Legume DM (t ha^{-1})	Total legume N uptake (kg ha^{-1})	Total weeds DM (t ha^{-1})	Total Weeds N uptake (kg ha^{-1})
CT	0.055c	1.37c	0.207b	3.74b
LRNiT	0.135b	3.36b	0.272b	5.12b
HRNiT	0.264a	6.73a	0.640a	12.66a
SED (10 df)	0.0356*	0.866*	0.128*	2.581*
BM	0.153ab	3.79ab	0.460a	5.88a
N_{us}	0.091b	2.37b	0.343a	6.75a
WC	0.210a	5.30a	0.316a	8.88a
SED (30 df)	0.0413*	1.08*	0.092 ^{ns}	1.992 ^{ns}

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05, ^{ns} p >0.05)*

2.4. Discussion for 2010/11 core experiment

Effects of different husbandry techniques on organic winter wheat performance

According to Nugis *et al.* (2009) crop establishment and early growth largely depends on seedbed conditions. In this study, difference in cultivation treatments that had created variation in seedbed conditions affected plant establishment. Seedbed conditions varied depending on pre-sowing tillage techniques, the type of drills used and the percentage of surface soil cover left after drilling wheat. Out of 410 seeds m^{-2} sown, maximum soil manipulation and complete dispersion of surface soil cover (CT) gave significantly higher plant establishment followed by minimal soil movements and 30% soil cover (LRNiT), compared with least soil movements and >50% soil cover (HRNiT). This indicates that the crop emergence was more favourable under higher levels of tillage intensity as a result of assumed increase in seed-soil contact. This observation supports Siemens & Wilkins (2006) and Wilkins *et al.* (1989) who demonstrated that fewer plants were obtained when wheat was drilled into seedbeds with reduced pre-plant tillage because of uneven seeding depth and poor seed-soil contact, compared with more tilled seedbeds.

According to Gooding *et al.* (2002) and Casal (1988) tillering ability is one of the most important traits of winter wheat, and plays a major role in determining winter wheat grain yield. Increase in tillering to compensate low plant population is often common in winter wheat (Whaley *et al.* 2000; Gooding *et al.* 2002; Lloveras *et al.* 2004). In the present study, on an average tiller per plant under CT appear to be 2.1, LRNiT 2.1 and HRNiT 1.9 (LSD 0.225^{ns}). This result indicates that the tillering was rarely influenced by contrasting cultivation treatments. However, the differences in cultivation treatments that determined the number of plants established per unit area also influenced the number of tillers, with CT having significantly higher tiller numbers per unit area followed by LRNiT, compared with HRNiT. Similar observation was also reported by Wade *et al.* (2006). Variation in tiller numbers, therefore, viewed not only on genotypes of the crop varieties, but also on the agricultural management and their impact on plant establishment, supporting Leaky (1971) and Baker & Briggs (1982).

Competition and compensation among wheat tillers often determines its survival and hence the formation of total fertile wheat shoots (Donald 1968; Windward *et al.* 1983). In this study, cultivation treatments that gave statistically higher plant establishment and tiller numbers with CT, had no effect (statistically non-significant) in determining the total number of shoots, compared with LRNiT. Initial lower plant establishment from LRNiT might have been compensated by either higher number of fertile shoots, or an increase in per-cent shoot survival, which could be the reason for statistically non-significant shoot density in comparison with CT. Similar observation of improved shoot survival at lower plant stand with conservation tillage relative to conventional tillage was reported by Spink *et al.* (2000). Whereas for CT, higher plant establishment and tiller numbers may have resulted in a lower production of fertile shoots, or a decrease in per-cent shoot survival, due to greater competition. Destro *et al.* (2001) also reported that higher plant densities and higher number of tillers might lead to negative wheat productivity, due to greater competition between tillers and their yield components. But, for HRNiT, tillage related greater variability in seedbed conditions that caused reduction in plant stand, might be the possible deterrent on total number of shoots, compared with LRNiT or CT.

The compensatory and competitive relationship that occurred between LRNiT and CT on shoot density possibly outweighed the tillage-induced variation on plant establishment. This observation supports Fischer (1984) who reported that total shoot densities and potential grain yield is believed to be consistent over a wide range of plant populations, because of the compensatory and competitive mechanism among tillers and their yield components in winter cereals.

Biomass production is the result of photosynthetic capacity (Olesen *et al.* 2003), and total biomass produced often gives a good indication of growth conditions during the crop cycle (Watson 1968). In this study, wheat DM between cultivation treatments varied throughout the mid-season assessments (Phase I, II, and III). Assessment at Phase I showed that CT developed significantly higher wheat DM than LRNiT or HRNiT. The difference in wheat DM might be due to the early variation on plant establishment and tiller numbers between cultivation treatments. However, at later assessments (Phase II and III), there were no statistically significant wheat DM differences, between CT and LRNiT. This might be due to the increase in number of fertile wheat shoots or improved per-cent shoot survival under LRNiT, prompting statistically equivalent wheat biomass to that of CT. Similar observation of lower wheat DM at early wheat growth stages and equivalent wheat DM at later growth stages with conservation tillage relative to conventional has been reported by Martinez *et al*. (2008). In their study, they reported that despite initial differences in plant populations and wheat biomass between tillage techniques, the better soil moisture status during insufficient rainfall periods prompted acceleration of growth under conservation tillage, resulting in even biomass and grain yields, compared with conventional tillage. Previous studies have also reported that under moderate rainfall conditions during the cropping season, although accumulation of wheat biomass generally favours conventional tillage, during periods of less rainfall or months of dry spells in a cropping year, crops grown under conservation tillage are less vulnerable (Crowley & Doring 2012; Arshad *et al.* 1999; Bonfil *et al.* 1999; De Vita *et al.* 2007; Martinez *et al.* 2008). It is so, because of better soil moisture status under reduced soil movements, and the presence of soil cover that can possibly reduce evaporation rate, compared to conventional tillage (Rasmussen 1999; Erenstein *et al.* 2008). In this study, despite soil moisture status not being directly assessed, it was noteworthy, considering the fact of less rainfall in early and mid-spring, although, wheat DM tends to be higher under CT than non-inversion tillage; the percentage increase of wheat DM from Phase II to Phase III was higher with LRNiT and HRNiT, compared with CT. This could be due to the variation in seedbed conditions and prevailing weather; wheat under non-inversion tillage systems might possibly had slower early crop growth than CT (Mehdi *et al.* 1999) due to lower temperature of the upper soil layers, because the seedbed conditions developed with non-inversion tillage systems is more compact and often remains moist more than with CT (Cannell 1985) and consequently it warms up. Thus in later assessments, the initial differences might have possibly deteriorated, and the growth and dry matter under LRNiT was statistically comparable with CT. This study, like many other studies (Crowley & Doring 2012; Martinez *et al.* 2008) reflect during periods of dry spells, the accumulation of wheat DM tends to increase under non-inversion tillage, compared with conventional ploughing. For HRNiT, despite wheat DM having increased, complexity in seedbed condition that caused lower plant populations resulted in significantly lower wheat DM, compared with LRNiT and CT.

The severity of weeds varied among tillage treatments. At both assessments, CT had significantly lower number of weeds followed by LRNiT, compared with HRNiT. The increase in levels of tillage intensity with complete dispersion of surface soil cover with CT might possibly the reason for significantly lower weeds number. This supports Hakansson (2003); Clements *et al.* (1996a) and Swanton *et al.* (2000) that a decrease in levels of tillage intensity without soil inversion, often results in greater weed pressure.

Generally, the earlier the emergence of weed relative to the crop the more competitive it is likely to be (Hakansson 2003). Lower weed environments when wheat is establishing is essential for successful organic crop production (Clements *et al.* 1996a). The difference in initial weed population between cultivation treatments however, did not show any statistically significant difference on total weeds DM at Phase II, III and final biological harvest, with CT and LRNiT having significantly lower total weeds DM, compared with HRNiT. The non-significant total weeds DM under LRNiT compared to that of CT might possibly due to the improved shoot survival that increased canopy size and ground cover. This condition might have resulted in greater shading of weeds supporting Richards (1989); Grundy *et al.* (1993); Christensen (1995); Samuel & Guest (1990) and Blackshaw (1993) who demonstrated that the competitive ability of wheat to reduce weed biomass has been related to plant height, biomass production, and crop ground cover. However, with HRNiT, lower plant populations, relatively reduced crop growth, and higher weed density at early crop growth stages, compared with CT and LRNiT may have resulted in greater total weeds DM throughout the growing season.

Most of the weeds species that were identified (HGCA 2010a) are commonly occurring weeds for winter wheat influenced more by crop type, environment, site location and time of year, as described by Derksen *et al.* (1993). Nevertheless, in this study, it was observed that the type of cultivation treatments employed influenced its composition, abundance, and biomass production. Thus contrasting cultivation treatments influencing the fate of weed species supports Mohler & Galford (1997) that the method, frequency, and intensity of tillage can have greater impact on the composition, population density, and long term persistence of the weed density. Although, assessment at Phase II, showed statistically non-significant tillage effects on broadleaf weeds DM, at Phase III, CT had significantly higher DM of broadleaf weeds, compared with LRNiT or HRNiT. This might be due to the increased probability of emergence of annual dicot weed species in spring and summer. Similar observation were also reported by Froud-Williams *et al.* (1983b) and Gill & Arshad (1995) that conventional ploughing increase annual broadleaf weed species in spring and summer than less disturbed soils. In contrast, throughout the growing season, grass weeds DM were significantly higher with HRNiT, compared with LRNiT or CT. The ability of most of the grass weeds to adapt and survive in less disturbed soils, compared to more tilled soils supports the view of Locke *et al.* (2002) and Hakansson (2003). Infestation and severity of wild oats and its removal also confirms that grass weeds were significantly favouring seedbeds with more limited soil movements such as HRNiT.

Development of *M. graminicola* was relatively under low levels due to less rainfall. Lower incidence of *M. graminicola* probably is the reason for non-significant difference in disease severity among cultivation treatments. The growth, establishment, and dry matter yield of undersown legumes were also greatly restricted in response to shortage of precipitation in spring. Similar observation of lower growth and dry matter production of undersown legumes due to insufficient rainfall was also reported by Gooding *et al.* (1998). However, among cultivation treatments, at Phase III and final biological harvest, legume DM were significantly higher with HRNiT followed by LRNiT, compared with CT. This might be explained by the recovery of previous ley under non-inversion tillage systems to which wheat was oversown, along with annual addition of legumes by undersowing that contributed to greater legumes DM than CT. Among undersowing, N_{us} was not completely free of legumes due to the natural regeneration of the previous ley. However, legume DM was significantly higher when WC was undersown than $N_{us.}$ Throughout the cropping season, BM was less vigorous compared to WC. Overall, the limited growth of undersown legumes has led to non-significant undersowing and tillage x undersowing effects on winter wheat yield and yield components, and also had no suppressive influence on weed communities.

Plant heights probably indicate the growing condition provided and often positively associated with final grain yield (Fischer 1985). Among three cultivation treatments, taller plant heights were obtained with CT and LRNiT than HRNiT. Acceleration of growth from LRNiT, along with reduced competition from weeds might possibly have resulted in statistically equivalent plant heights to that of CT. Similar observation was also reported by Martinez *et al*. (2008). However, for HRNiT lower early crop growth and greater weed burden might have substantial negative impact on plant heights. Similar observation was also reported by Clements *et al.* (1996a) and Gooding & Davies (1997) that competition from weeds especially grass weeds is more likely to reduce crop vigour.

Previous studies have reported that ears per unit area as the main determinants of wheat yield (Prew *et al.* 1985; Thorne & Wood 1987; Donaldson *et al.* 2001). Number of ears per unit area reportedly varies according to agricultural management and its impact on plant establishment, tiller production, and its survival (Mc-Master *et al.* 1994). Accordingly, in this study, the number of ears per unit area was highly related to the cultivation-induced resultant effects on total number of shoots. Implying that CT and LRNiT that had statistically comparable shoot density also resulted in statistically equivalent ear numbers than HRNiT, despite HRNiT appear to have lower shoot mortality rate than other treatments. Taller plant heights and greater ear numbers from CT and LRNiT also resulted in greater DM of straw and ears, compared with HRNiT. This observation supports Halvorson *et al.* (2002) and Latta & O' Leary (2003).

Responses of cereal grain yields to different cultivation treatments was, therefore, variable due to the complex interactions between tillage induced-seedbed conditions, weed competition, and weather events, supporting Boone (1988); Rao & Dao (1996) and Rasmussen *et al.* (1997). In this study, the different cultivation treatments that caused direct effects on plant establishment, had no effect in determining the outcome of crop yield between CT and LRNiT. Grain yield was significantly higher with CT and LRNiT than HRNiT. LRNiT, despite lower early plant establishment and tiller numbers, higher number of fertile shoots or improved shoot survival that potentially accelerated the field performance as comparable (statistically) with CT, also prompted statistically equivalent TGW and grain yield with CT. These observations supports Halvorson *et al.* (2002); Latta & O' Leary (2003); Gursoy *et al.* (2010) that the tillage systems influencing early variation in plant populations did not affect the final winter cereal grain yield. Throughout the growing season, HRNiT that had lower plant numbers, reduced crop growth and greater weeds competition, resulted in fewer grain yields, compared with LRNiT or CT. This supports Wilkins *et al.* (1989) and Graven & Carter (1991) who demonstrated that less soil movements and retention of maximum amounts of soil cover can cause negative effects on plant establishment and subsequent crop yields.

In the present study, the stress condition between wheat and contrasting tillage treatments that had greater impact on yield and its components, had no significant influence on grain protein content. Similar observation was also reported by Baenzinger *et al.* (1985); Bassett *et al.* (1989); Cox & Shelton (1992). Furthermore, factors (seeding rate, crop variety, and weather conditions) which have increased grain yield potential often decrease grain protein content. This might be due to the reported inverse relationship between grain protein levels and yield (Lopez-Bellido *et al.* 1998; Blackman & Payne 1987; Smith *et al.* 2006; Kindred *et al.* 2007). Although, weeds competition was higher under non-inversion tillage such as HRNiT, no significant difference in N% of weeds or wheat was observed among tillage treatments. This situation making it difficult to describe whether weed infestation possibly might have any impact on main crop performance or grain protein content. Nevertheless, based on the results, it appears that the protein concentration is more influenced by environment and crop genotypic factors beyond agricultural management practices, supporting Fowler *et al.* (1990).

2.5. Summary

The initial investigation with winter wheat, demonstrated the importance of seedbed conditions in determining either the development or hindrance to plant establishment, and following crop growth. The success among tillage treatments was initially determined by the plant establishment and secondly, by total number of shoots formed per unit area, and finally the aggressiveness of weeds. Although plant establishment and tiller numbers were significantly higher with CT than other treatments, the competitive and compensatory relationship that occurred between CT and LRNiT on total number of shoots had potentially outweighed the tillage-induced effects on initial plant populations. This condition is of greater importance as Fischer (2007) described that on an average 30% to 50% of the grain yield of winter wheat comes from the main stem and 50% to 70% comes from the tillers. Accordingly, the crop productivity was statistically comparable between CT and LRNiT. Greater shoot densities with CT and LRNiT facilitated higher ground cover, which also considerably reduced total weeds DM, as reported by Richards (1989) and Samuel & Guest (1990). In contrast, maximum decrease in tillage intensity with greater retention of soil cover with HRNiT not only affected the plant populations but also provided conditions for increased weeds emergence due to reduced main crop competitive ability. This situation significantly reduced the wheat performance under HRNiT, compared with CT or LRNiT. This supports Sprague & Triplett (1986) who reported that the retention of greater crop residues due to maximum reduction in tillage intensity can cause variable crop growth, thereby reducing primary crop competitive ability, resulting in fewer grain yields. Effects of these cultivations on wheat biomass and ground cover, therefore, can be a possible indicator of predicting crop yield, and its competitive ability against weeds supporting Kumudini *et al.* (2008) and Balyan *et al.* (1991).

Difference in cultivation treatments also influenced the DM of weed species. Significantly higher broadleaf weeds were obtained with CT than non-inversion tillage systems, and significantly higher grass weeds obtained with HRNiT than CT or LRNiT. The increase in levels of tillage intensity reduced grass weeds DM and hence total weeds DM. These observations reconfirm Hakansson (2003); Colbach *et al.* (2005); Froud-Williams *et al.* (1983b); Locke *et al.* (2002).

Under the soil and weather conditions that prevailed, on the basis of field and yield performance, LRNiT seems to be an acceptable alternative to CT. This supports Crowley & Doring (2012); Bonfil *et al.* (1999) and Martinez *et al.* (2008) who all demonstrated equivalent performance of wheat with conservation tillage, compared with conventional tillage under insufficient rainfall in a cropping year. Thus, the initial study was encouraging in terms of adopting non-inversion tillage in particular, LRNiT for organic winter wheat production after fertility-building phase. However, with weather uncertainty and increasing recognition of spring wheat for its rotational benefits and good premium opportunities, further experimental study was conducted. Unlike winter wheat, spring wheat with few tillers and shorter growing season, various husbandry practice-induced effects on yield components and yield could be studied more comprehensively. The behaviour of weed flora can also be further investigated to reinstate the trend observed. Furthermore, the evaluation of soil related properties could also provide a wider understanding of overall causes and benefits of adopting various organic husbandry practices.

Chapter – 3

CORE EXPERIMENT - II: PERFORMANCE OF ORGANIC SPRING WHEAT FOLLOWING DIFFERENT CULTIVATION SYSTEMS AND LEGUME UNDERSOWING

3.1 Introduction to 2012 core experiment

In this study of continuous organic cereal legume-cereal intercrops, undersowing was chosen as the method to establish a cover crop that might be competitive against weeds. This thought to be a suitable method, supporting Schroder (2001) who reported that when cover crop is sown later which would be after cereal harvest, the weather conditions during autumn may not be reliable for satisfactory growth. Furthermore, cereal crop performance following cereal legume-cereal intercrops is usually better than those of continuous cereal cropping (Fujita *et al.* 1992; Galantini *et al.* 2000). Against this background, after the harvest of winter wheat on 25 August 2011, the field was left with soil cover. The soil cover varied predominately from previous wheat straw, white clover and black medic to grass and broadleaf weeds. It was thought that the ability of legume to put on new growth after winter wheat harvest might possibly help to prevent de-nitrification losses and could potentially act as catch crops to accumulate nitrogen (Jones 1992; Jensen 1991) to benefit following 2012 spring wheat. The dense legume canopy that might develop over the period, before drilling 2012 spring wheat could also potentially be effective in controlling weeds and diseases (Breland 1996; Clements & Donaldson 1997). However, the ability of legume cover crops to increase its biomass and concerns over poor competitive ability with weeds, may also negatively affect succeeding crop yield (Biederbeck *et al.* 1996; Nielsen & Vigil 2005).

The experiment was repeated with spring wheat. Spring wheat varieties are often known for their rotational benefits; are better able to exploit shorter seasons and can cope with stress during the early season (NABIM 2013). Kankanen *et al.* (2001) and Garand *et al.* (2001) reported that spring wheat has good ability to grow well with an undersown crop, because of its higher early growth rate and height advantage. Similarly, Kirkegaard *et al.* (1994) and Lopez-Bellido *et al.* (1998) demonstrated that the inclusion of legume intercrops increased wheat yields and protein content, compared to monoculture. In contrast, Jones & Clements (1993) found that spring wheat was unable to compete in a bi-cropping environment. In this study, therefore, the aim is to further explore the influence of cultivation and undersowing treatments on the field and yield performance of spring wheat. Additionally, soil properties were also characterised to better try to understand the crop performance among various husbandry techniques.

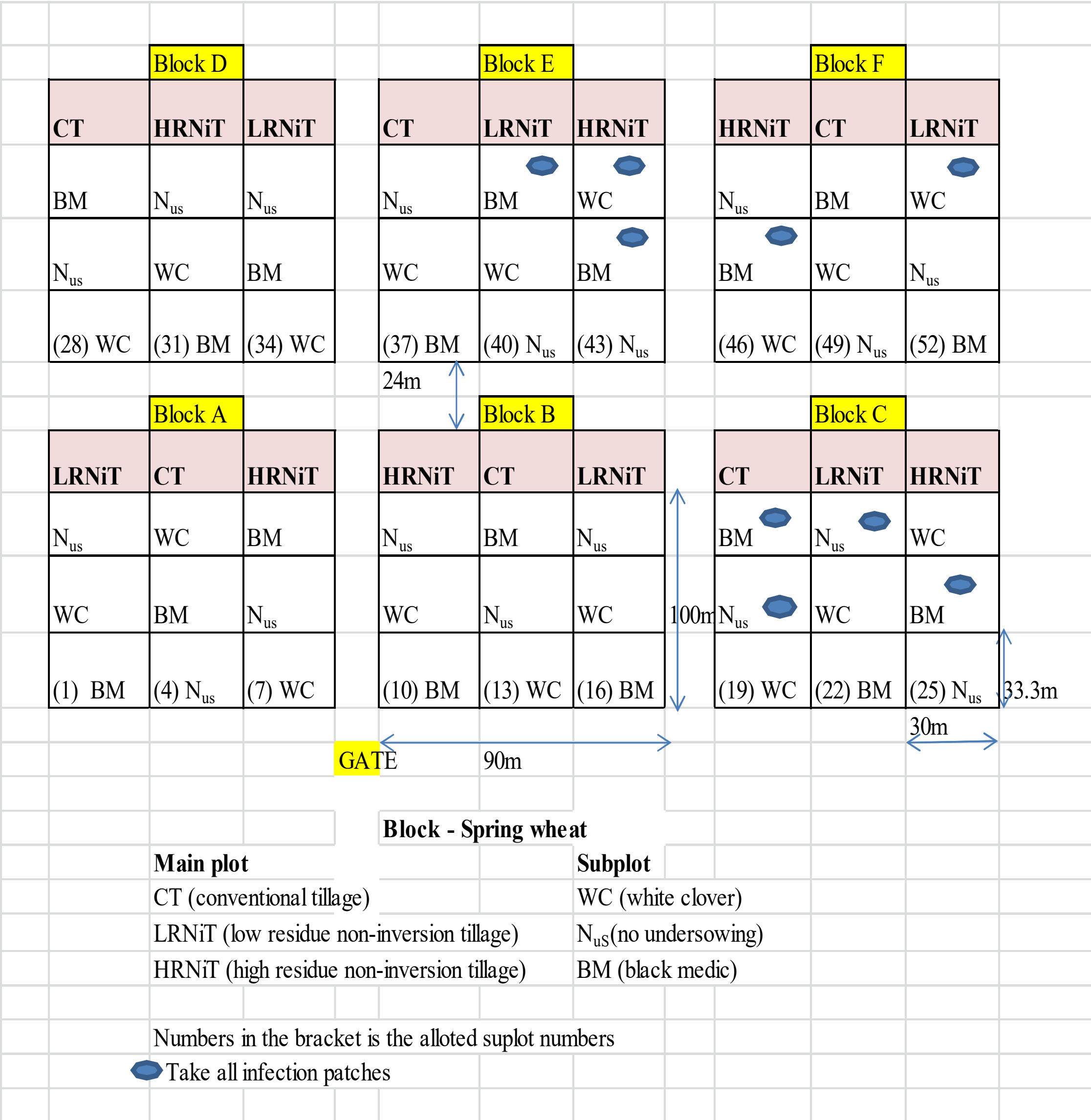
3.2 Materials and Methods for 2012 core experiment

3.2.1 Experimental design and treatment structure

The study was conducted from March 2012 to August 2012 on a field previously cropped with organic winter wheat cv. Claire. The experimental design was the same as that described previously and using the existing experimental design structure (Chapter – 2, core experiment – I, §2.2.3). Three different (CT, LRNiT, and HRNiT) land preparation techniques was commenced on 09 March 2012, and spring wheat cv. Paragon at 420 seeds m^{-2} was drilled on 14 March 2012. Undersowing treatments were established on 10 April 2012 and the trial was harvested on 22 August 2012. The treatment structure (Figure 3.1) was a full factorial of:

Spring wheat (block) ***x*** *tillage systems (main plot)* ***x*** +/- *undersowing (subplot)*

Figure 3.1 Trial design for organic spring wheat 2012



Varietal choice

The wheat variety under organic farming conditions was considered with particular attention given to bread-making quality and disease resistance (Lammerts van Bueren *et al.* 2010; Li *et al.* 2010). Group 1 (bread-making/milling) - spring wheat cv. Paragon was chosen, as it has good standing power, resistance to shedding, good disease resistance and long, relatively stiff straw. Paragon have been reported to produce grains with high protein content and enables grains quality to be maintained even under untreated trial conditions (NABIM 2013).

Sowing date

Variation in sowing date can have significant influences on plant characteristics and grain yield of wheat (Hayward 1990). Variation in weather patterns across season to season means there can be no chosen time for sowing. Therefore, sowing date for the present study was adjusted according to pre-sowing cultivation and weather events in particular, precipitation patterns. Nevertheless, drilling wheat into existing surface soil cover (from the previous cropping year) under non-inversion tillage systems can possibly result in greater competition for the cereal. This might affect crop establishment and cause reduced yields (Siemens *et al.* 2004; Gooding *et al.* 1998).

Seed rate and drilling depth

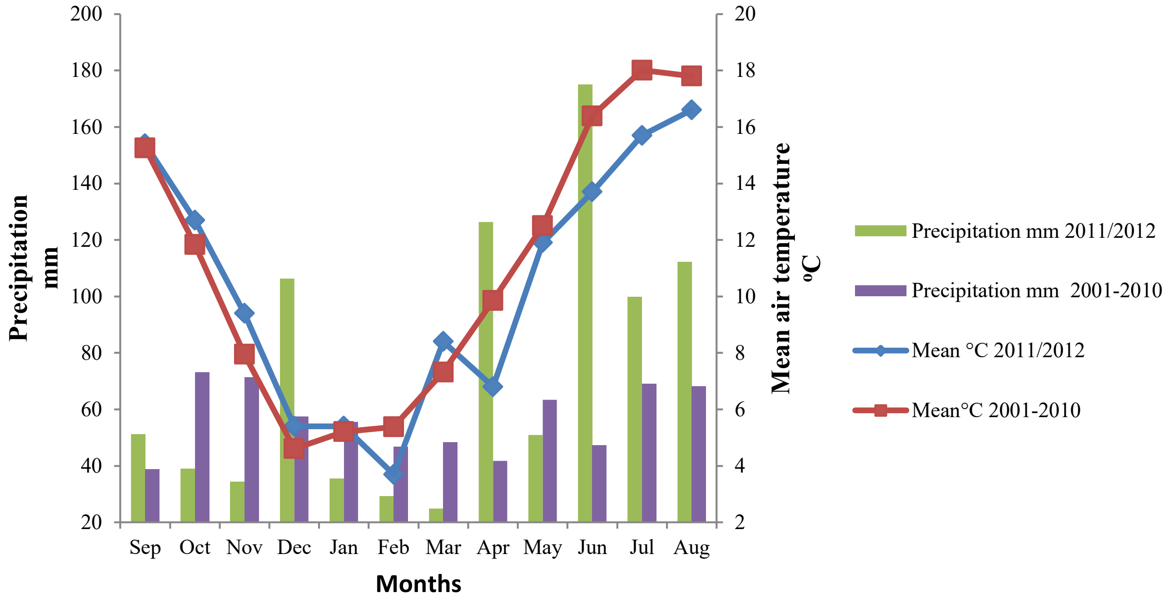
Seed rate varies greatly according to sowing date, climatic conditions, soil type, and cultivars (Anderson & Barclay 1991; Tompkins *et al.* 1991). Genotypes of spring wheat varieties with low tillering capacity, particularly under organic farming conditions, should be complemented with high plant density to produce an optimum number of competitive plants (Lithourgidis *et al.* 2006; Arduini *et al.* 2006). In the UK, most organic spring wheat growers use seeding rate of ≥500 seeds m^{-2} (Lampkin *et al.* 2011). However, to study the influence of different husbandry practices, a relatively similar seeding rate to that of winter wheat (≥400 seeds m^{-2}) was opted. Likewise, drilling depth of 2cm and coulter row spacing of 12.5cm was maintained for all combination seed drills. However, drills may perform differently based on pre-sowing cultivation.

3.2.2 Meteorological conditions

The autumn and winter 2011/2012 recorded an average air temperature of 8.7^{o}C and precipitation of 295.6mm.

The 2012 cropping year (March to August 2012) recorded an average air temperature of 12.2^{o}C and a precipitation of 589.1mm. During the cropping season, the maximum and minimum air temperature was recorded in the month August (16.6^{o}C) and April (6.8^{o}C). Maximum and minimum rainfall received was in the month June (175mm) and March (24.9mm). The 2012 of spring wheat vegetation period experienced lower spring and summer time average air temperatures, and precipitations were much higher throughout the growing season, compared to long-time seasonal average (Figure 3.2).

Figure 3.2 Mean air temperature and amount of precipitation during 2011/12 crop season. Royal Agricultural University Meteorological station, (NGR SP 42 004 011)



3.2.3. Assessments

<u>Soil assessments</u>

Soil mineral nitrogen (SMN) was assessed using potassium sulphate (K_2SO_4) extraction method. Soils were sampled to a depth of 25cm at twenty randomly selected positions within each subplot at monthly intervals beginning from 21 February 2012 using Dutch auger core of 3cm diameter, and bulked to form a representative samples. Soil samples were immediately placed in plastic bags after collection and all samples were processed within 24hr of arrival in the laboratory. The laboratory processing of samples involved, the bulked soil from each subplot which was thoroughly hand mixed, crumbled and passed through a 6.7mm sieve. Any plant material or visible stones were removed. Three analytical replication of each sample was weighed 25g (+/- 0.02g) onto a tarred weigh-boat and transferred to a labelled extraction bottle. 100ml of 0.5M K_2SO4 was treated into each labelled extraction bottle, including three blanks in each extraction batch. The extraction bottle with the blanks was then shaken on a Gerhardt

Laboshake Large Orbital Shaker 115 VAC (C. Gerhardt UK Ltd) at 200 oscillations per minutes for 30 minutes and allowed to stand with loosen tops for 15mins. The suspension was then filtered through Whatman No. 40 filter paper and the extract was collected after discarding the initial 3 drops. The collected extracts were placed in bag with name, site, and date of sampling, and then stored frozen for analysis using FiAstar^{TM} 5000 system (FIA), based on flow injection analysis and colorimetric methods. Simultaneously, dry matter was analysed by weighing fresh soil samples 50g (+/-0.05g) from each subplot and oven dried at 100^{o}C overnight. Soil moisture percentage (gravimetric) was estimated using the formula (soil wet weight – soil dry weight) / (soil dry weight) * (100) (Brady & Weil 1999). The remainder of the sample was air dried and used for soil chemical analysis. SMN was estimated using the following formula and for the purpose of calculation, bulk density value of 1.1gcm^{-3} (USDA 2008) was considered and applied across all the treatments.

$$\text{Soil mineral N (mg kg}^{-1}\text{)} = \left[\frac{\frac{\text{(Extraction volume (ml) x extract mineral N (mg/l)}}{1000}}{\text{(Soil dry weight (g)/1000)}} \right]$$

$$\text{Soil mineral N (kg ha}^{-1}\text{)} = \left(\text{Soil mineral N (mg kg}^{-1}\text{) x bulk density x depth factor} \right)$$

Soil penetration resistance measurements were made at 5cm, 10cm, 15cm, and 25cm soil depth using a hand penetrometer (model - 06.01.SA, Eijkelkamp, Giesbeek, Netherlands) at ten randomly selected positions from each subplot after cultivation or during wheat emergence (27 March 2012). The cone type was 60^{o} angle with 3.33cm^{2} base area. The penetrometer consists of a measuring instrument, a probing rod, and a cone. The device is pushed perpendicular into the soil and the resistance is read in N (Newton) and noted for appropriate depth. The cone resistance was estimated by the ratio of manometer reading (N) to the base area (cm^{2}). For calculation purpose 100Ncm^{-2} = 1000 KNm^{-2} or 1000 kPa = 1MPa.

Air dried samples after tillage (21 April 2012), during the vegetation period (21 June 2012) and before harvest (21 August 2012) from a depth of 0-25cm were used for chemical analysis: soil pH, soil organic carbon (C_{org}), soil total nitrogen (N_t), soil phosphorus (P) and soil potassium (K). Soil pH was analysed by weighing 20g of soil samples (three replications per subplot) onto a tarred weigh-boat and then transferred to the labelled shaking bottles. Then 50 ml of deionised water were dispensed into each shaking bottles. The shaking bottles were then shaken on a Gerhardt Laboshake Large Orbital Shaker 115 VAC (C. Gerhardt UK Ltd) at 200 oscillations per minutes for 15 minutes. Then using the pH meter, the readings were measured on the suspension.

The Olsen Method was used to measure soil P. Soil samples from each subplot (three replications) were weighed (5g) onto a tarred weigh-boat and then transferred to the labelled 150ml shaking bottles. Then a scoopful of powdered charcoal and 100ml of sodium bicarbonate was added to the shaking bottles. The bottles were shaken on a Gerhardt Laboshake Large Orbital Shaker 115 VAC (C. Gerhardt UK Ltd) at 200 oscillations per minutes for 30 minutes and filtered through Whatman No. 2 filter paper. The 5ml filtrate was added to a 100ml conical flask using a pipette, and then 1ml of sulphuric acid was added. After swirling the contents to release carbon dioxide, 20ml of ammonium molybdate/ ascorbic acid was added and the mixture was allowed to stand for 30 minutes. Absorbance value was then read using a spectrophotometer.

Soil K was measured by ammonium nitrate extraction. Soil samples from each subplot (three replications) were weighed (10g) onto a tarred weigh-boat and then transferred to the labelled 150ml shaking bottles. 50ml ammonium nitrate (400g ammonium nitrate in 4L deionised water) was added and then shaken for 30 minutes (200 oscillations per minute) on a Gerhardt Laboshake Large Orbital Shaker 115 VAC (C. Gerhardt UK Ltd). The suspension was then filtered through Whatman No. 2 filter paper and concentrations of K measured using the flame photometer. Emissions were converted to part per million (ppm) using the computer programme (units of emission x 5).

Soil total nitrogen (N_t) and soil total carbon (C_t) were measured using the Elementar cube auto analyser. Subsamples of air dried soil that had been sieved through 2mm sieve were fine-milled using a Micro hammer-cutter (Glen Creston Micro-mill Ltd) mill to sieve through a 0.5mm sieve (nickel screen). For each sample, using five place analytical balance 50mg (± 0.05 mg) of well mixed sample plus 50mg of Tungsten oxide was weighed into aluminium foil. The foil was carefully capsulated using forceps, and the sample was analysed using an Elementar Cube auto analyser (Elementar Analysensysteme GmbH). Soil organic carbon (C_{org}) was later obtained by subtracting the % of soil inorganic carbon (through a Calcimeter technique) from soil total carbon (C_t).

Earthworm numbers were assessed using hand sorting method (Edwards & Bohlen 1996) - three replications per subplot by removing samples of soil using a quadrat of size 25cm x 25cm and depth 20cm after tillage (10 April 2012), during vegetation period (18 June 2012) and before harvest (15 August 2012).

Above ground assessments

2012 spring wheat above ground assessments (Table 3.1) conducted using the same protocol and formula as in Chapter – 2, core experiment – I, §2.2.4.

Table 3.1 Above ground assessments for spring wheat 2012

Assessments	Sample size	Date/Approximate growth stages
Legumes and total weeds biomass before cultivation	0.25m^2 quadrat randomly with five replications per subplot	26 February 2012
Wheat establishment	0.25m^2 quadrat randomly with ten replications per subplot	29 March 2012
Wheat tiller numbers	0.25m^2 quadrat randomly with ten replications per subplot	15 April 2012
Wheat total shoot numbers	0.25m^2 quadrat randomly with ten replications per subplot	25 April 2012 and 14 May 2012
Growth assessments	Hand harvested randomly using a 0.25m^2 quadrat with five replications per subplot. Samples separated as wheat, legumes (white clover or black medic) and total weeds (specifically broadleaf or grass weeds, only at Phase II and Phase III)	29 April 2012 (Phase I), 29 May 2012 (Phase II), and 20 June 2012 (Phase III)
Wheat plant heights	Rising disk apparatus. Twenty random measures per subplot	25 July 2012
Wheat ear numbers	0.25m^2 quadrat randomly with ten replications per subplot	21 July & 06 August 2012

Mycosphaerella graminicola	Twenty wheat shoots sampled at ten random points per subplot and top three leaves were monitored	05 July 2012
Take-all infection patches	Using 0-3 index. 0 = take all patch were not evident; 1 = consist of relatively inconspicuous patches; 2 = characteristics patches with thin and yellowing of wheat plants 3 = consist of well-defined patch, stunted, developed white (bleached heads) and easily pulled out (adopted and modified from Scott & Hollins 1974).	02 July 2012
Sooty mould and Fusarium infected ears	0.25m^2 quadrat randomly with ten replications per subplot	14 July 2012
Final biological harvest	0.25m^2 quadrat randomly with five replications per subplot	22 August 2012

Continuation of Table 3.1

3.2.4. Data analysis

Statistical analysis and reporting results, as stated in Chapter – 2, core experiment – I, §2.2.5. The number of ears infected with sooty mould and fusarium were transformed using LOG10 (n + 1) (n = infected ear numbers) to reduce heterogeneity of variance. Repeated measurements ANOVA were performed to validate changes in treatment effects over time (in particular, for soil chemical and earthworm assessments). Although significant differences ($p < 0.05$) were observed at each time of assessment, the combined repeated measurements analysis was non-significant ($p > 0.05$). Implying that the differences at each time of assessment were the same or perhaps, not changing from time to time for the treatment effects x time interaction to be significant. Hence mean values were reported for the treatments.

3.3. Results for 2012 core experiment

Legume biomass and nitrogen accumulation overwinter 2011

Before 2012 cultivation, the overwinter assessment showed that non-inversion tillage systems had significantly higher legume DM than CT (Table 3.2). Total legumes N uptake among tillage treatments showed a similar trend to that of legumes DM. Among undersowing, WC had significantly higher legume DM followed by BM, compared with $N_{us.}$ Total legume N uptake was significantly higher with WC, compared with BM or $N_{us.}$ There was no statistically significant tillage x undersowing interaction on legume DM or total legume N uptake.

Table 3.2 Legume biomass and nitrogen yields - overwinter 2011

	Legume DM ($t\ ha^{-1}$)	Total legume N Uptake ($kg\ ha^{-1}$)
CT	0.261b	9.20b
LRNiT	0.360a	14.09a
HRNiT	0.438a	15.37a
SED (10 df)	0.0368*	1.79*
BM	0.347b	12.43b
N_{us}	0.254c	8.96b
WC	0.458a	17.27a
SED (30 df)	0.0437*	1.89*

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05)*

Weeds biomass and nitrogen accumulation overwinter 2011

Before 2012 cultivation, the overwinter assessment showed that CT and LRNiT had significantly lower total weeds DM, than HRNiT (Table 3.3). Total weeds N uptake among tillage treatments showed a similar trend to that of weeds DM. Among undersowing, total weeds DM and therefore the total weeds N uptake was significantly lower with WC than BM or $N_{us.}$ There was no significant tillage x undersowing interaction on weeds DM or total weeds N uptake.

Table 3.3 Weeds biomass and nitrogen yields - overwinter 2011

	Total Weeds DM (t ha^{-1})	Total weeds N uptake (kg ha^{-1})
CT	0.304b	5.36b
LRNiT	0.392b	6.85b
HRNiT	0.568a	12.32a
SED (10 df)	0.0671*	2.24*
BM	0.438a	8.39a
N_{us}	0.446a	9.14a
WC	0.380b	7.00b
SED (30 df)	0.0150*	0.648*

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05)*

Soil penetration resistance

Soil penetration resistance were assessed mainly to recognize the difference in seedbed conditions as a measure of plant growth. Assessment after cultivation or during wheat emergence (27 March 2012) (Table 3.4) revealed that CT and LRNiT had significantly lower penetration resistance than HRNiT at 5cm, 10cm and 15cm soil depth. Despite lower penetration resistance, with CT and LRNiT at 25cm soil depth, there were no statistically significant tillage effects. These results indicate that more tillage intensity lowers soil resistance near the surface soil layers.

Table 3.4 Effect of tillage treatments on soil penetration resistance (2012)

	5cm	10cm	15cm	25cm
CT	560b	690b	831b	964a
LRNiT	637b	754b	877b	1012a
HRNiT	901a	1008a	1077a	1126a
SED (10 df)	36.67*	54.40*	48.26*	75.00 ^{ns}

*Penetration resistance (in kPa) measured at late March at different soil depth. For each depth, values followed by the same letter do not differ significantly (*p <0.05, ^{ns} p >0.05)*

Plant establishment and tiller numbers

Wheat establishment was significantly higher with CT followed by LRNiT, compared with HRNiT (Table 3.5). Contrasting cultivation treatments that affected plant establishment also showed a similar influence on tiller numbers.

Table 3.5 Wheat field performance under three tillage treatments (2012)

	Establishment (counts m^{-2})	Tiller (numbers m^{-2})
CT	277a	356a
LRNiT	214b	235b
HRNiT	170c	183c
SED (10 df)	18.66*	20.78*

*Values followed by the same letter do not differ significantly (*p <0.05)*

Total shoots

At each time of assessment, cultivation treatments that affected plant establishment and tiller numbers, also influenced total number of wheat shoots, with CT having significantly higher number of shoots, compared with LRNiT or HRNiT. Among undersowing treatments, at both assessments, N_{us} had significantly higher total number of wheat shoots than BM. The mean values were therefore, reported (Table 3.6) for tillage and undersowing treatments. Throughout the assessments, there was no statistically significant cultivation x undersowing interaction on total number of wheat shoots.

Table 3.6 Shoot density under different husbandry treatments (2012)

	Shoot (total numbers m^{-2}) *(mean values)*
CT	554a
LRNiT	398b
HRNiT	288c
SED (10 df)	45.1*
BM	373b
N_{us}	445a
WC	422ab
SED (30 df)	25.2*

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05)*

Wheat biomass and nitrogen accumulation

Assessment at Phase I (Table 3.7) resulted in CT having significantly higher wheat DM than HRNiT. However, at Phase II and III, wheat DM was significantly higher with CT than LRNiT or HRNiT. Among undersowing treatments, at Phase II and III, N_{us} had significantly higher wheat DM than BM.

Among cultivation treatments, at each time of assessment (Table 3.8) total wheat N uptake showed a similar trend to that of wheat DM. Among undersowing treatments, at Phase II and III, BM had significantly lower total wheat N uptake than WC or N_{us}. Although, wheat DM between BM and WC did not vary significantly at Phase II and III, the wheat N uptake varied statistically. This might possibly be due to the slightly higher N % with WC than BM (although N % was statistically non-significant between undersowing treatments). Throughout the assessments, there was no significant cultivation x undersowing interaction on wheat DM or total wheat N uptake.

Table 3.7 Wheat biomass under different husbandry treatments (2012)

	Wheat DM (t ha^{-1}) Phase I	Wheat DM (t ha^{-1}) Phase II	Wheat DM (t ha^{-1}) Phase III
CT	0.226a	2.74a	6.60a
LRNiT	0.164ab	2.28b	5.33b
HRNiT	0.120b	1.46c	3.42c
SED (10 df)	0.0312*	0.176*	0.244*
BM	0.146a	1.85b	4.55b
N_{us}	0.183a	2.40a	5.52a
WC	0.181a	2.23ab	5.28ab
SED (30 df)	0.022^{ns}	0.194*	0.382*

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05, ^{ns}p >0.05)*

Table 3.8 Wheat nitrogen yields under different husbandry treatments (2012)

	Total wheat N uptake (kg ha^{-1}) Phase I	Total wheat N uptake (kg ha^{-1}) Phase II	Total wheat N uptake (kg ha^{-1}) Phase III
CT	10.48a	52.03a	78.74a
LRNiT	7.45ab	40.81b	57.92b
HRNiT	5.26b	26.92c	36.62c
SED (10 df)	1.61*	3.35*	6.79*
BM	6.69a	32.51b	49.6b
N_{us}	8.21a	45.02a	61.8a
WC	8.30a	42.20a	62.6a
SED (30 df)	1.08^{ns}	3.83*	5.09*

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05, ^{ns}p >0.05)*

Legume biomass and nitrogen accumulation

Assessment at Phase I (Table 3.9) showed that HRNiT had significantly higher legume DM followed by LRNiT, compared with CT. However, at Phase II and III, LRNiT and HRNiT had significantly higher legume DM than CT. Among undersowing treatments, N_{us} was not completely free of legumes due to the natural regeneration of previous ley. At Phase I, WC had significantly higher legume DM than BM or N_{us}. However, at Phase II, legume DM was significantly higher with WC followed by BM, compared with $N_{us.}$ But at Phase III, WC and BM had significantly higher legume DM than $N_{us.}$

Total legume N uptake (Table 3.10) among tillage treatments showed a similar trend to that of legume DM. However, for undersowing treatments, total legume N uptake varied besides the variation in legume DM. At Phase I and II, total legume N uptake was significantly higher with WC than BM or $N_{us.}$ However, at Phase III, total legume N uptake was higher with WC followed by BM, compared with $N_{us.}$ The variability of N % (although statistically non-significant) may be the reason for variation in total legume N uptake, besides legume DM. Throughout the assessments, there was no significant cultivation x undersowing interaction on legume DM or total legume N uptake.

Table 3.9 Legume biomass under different husbandry treatments (2012)

	Legume DM ($t\ ha^{-1}$) Phase I	Legume DM ($t\ ha^{-1}$) Phase II	Legume DM ($t\ ha^{-1}$) Phase III
CT	0.049c	0.104b	0.160b
LRNiT	0.139b	0.440a	0.566a
HRNiT	0.229a	0.543a	0.707a
SED (10 df)	0.0202*	0.106*	0.117*
BM	0.123b	0.362b	0.494a
N_{us}	0.076b	0.199c	0.282b
WC	0.218a	0.525a	0.659a
SED (30 df)	0.0358*	0.078*	0.088*

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05)*

Table 3.10 Legume nitrogen yields under different husbandry treatments (2012)

	Total legume N uptake (kg ha^{-1}) Phase I	Total legume N uptake (kg ha^{-1}) Phase II	Total legume N uptake (kg ha^{-1}) Phase III
CT	1.41c	2.55b	3.65b
LRNiT	3.78b	10.91a	13.81a
HRNiT	6.09a	13.05a	16.87a
SED (10 df)	0.586*	2.612*	3.078*
BM	3.09b	8.36b	11.28b
N_{us}	2.08b	4.97b	6.88c
WC	6.10a	13.18a	16.17a
SED (30 df)	0.969*	1.810*	2.081*

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05)*

Total weeds biomass and nitrogen accumulation

Throughout the mid-season assessments (Phase I, II and III), HRNiT had significantly higher total weeds DM than CT or LRNiT (Table 3.11). Among undersowing, WC had significantly lower total weeds DM than BM. At each time of assessment, total weeds N uptake (Table 3.12) followed a similar trend to that of weeds DM for tillage and undersowing treatments. There was no significant cultivation x undersowing interaction on total weeds DM or total weeds N uptake at each time of assessment.

Table 3.11 Total weeds biomass under different husbandry treatments (2012)

	Weeds DM (t ha^{-1}) Phase I	Weeds DM (t ha^{-1}) Phase II	Weeds DM (t ha^{-1}) Phase III
CT	0.0139b	0.104b	0.291b
LRNiT	0.0706b	0.191b	0.563b
HRNiT	0.246a	0.617a	1.375a
SED (10 df)	0.0497*	0.090*	0.202*
BM	0.121a	0.408a	0.909a
N_{us}	0.116a	0.318ab	0.776ab
WC	0.0936b	0.186b	0.544b
SED (30 df)	0.0071*	0.077*	0.121*

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05)*

Table 3.12 Total weeds nitrogen yields under different husbandry treatments (2012)

	Total weeds N uptake (kg ha^{-1}) Phase I	Total weeds N uptake (kg ha^{-1}) Phase II	Total weeds N uptake (kg ha^{-1}) Phase III
CT	0.256b	1.49b	3.75b
LRNiT	1.316b	2.86b	7.83b
HRNiT	5.009a	8.91a	18.80a
SED (10 df)	1.046*	1.273*	2.548*
BM	2.42a	5.78a	12.72a
N_{us}	2.36a	4.86ab	10.33ab
WC	1.81b	2.62b	7.33b
SED (30 df)	0.185*	1.229*	1.819*

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05)*

Weed species composition

Irrespective of cultivation or undersowing treatments, broad leaf weeds throughout the cropping season were *Matricaria recutita* (scented mayweed), *Tripleurospermum inodorum* (scentless mayweed), *Viola arvensis* (field pansy), *Veronica hederifolia* (ivy leaved speedwell), *Veronica persica* (common field-speedwell), *Stellaria media* (chickweed), *Galium aparine* (cleavers), *Fallopia convolvulus* (black-bind weed), *Aethusa cynapium* (fool's parsley), *Sinapis arvensis* (charlock), *Cirsium arvense* (creeping thistle), *Rumex obtusifolius* (broad-leaved dock), *Chenopodium album* (Fat hen) *Polygonum aviculare* (knot grass) and *Lamium purpurem* (red dead nettle). The grass weeds were *Avena fatua* (wild oat), *Lolium perenne* (perennial rye grass), *Poa annua* (annual meadow grass), and *Poa trivialis* (rough-stalked meadow grass).

At both assessments (Phase II and III) (Table 3.13) broadleaf weeds DM were significantly higher with CT than HRNiT whereas, grass weeds DM were significantly higher under HRNiT than LRNiT or CT. Among undersowing treatments, WC had significantly lower broadleaf weeds DM than BM or N_{us}. There were no statistically significant undersowing treatments effects on grass weeds DM, despite WC showed lower values. Throughout the assessments, there was no statistically significant cultivation x undersowing interaction on weeds species DM.

Table 3.13 Weed species biomass under different husbandry treatments (2012)

	Broadleaf DM (t ha^{-1}) Phase II	Grass DM (t ha^{-1}) Phase II	Broadleaf DM (t ha^{-1}) Phase III	Grass DM (t ha^{-1}) Phase III
CT	0.0638a	0.040b	0.180a	0.111b
LRNiT	0.0506ab	0.140b	0.147ab	0.416b
HRNiT	0.0279b	0.589a	0.085b	1.290a
SED (10 df)	0.0125*	0.0947*	0.0338*	0.191*
BM	0.0585a	0.349a	0.158a	0.751a
N_{us}	0.0534a	0.264a	0.167a	0.609a
WC	0.0304b	0.155a	0.087b	0.457a
SED (30 df)	0.0081*	0.0951 ^{ns}	0.0190*	0.147 ^{ns}

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05,* ^{ns} *p >0.05)*

Mycosphaerella graminicola

The 2012 cropping year with warm temperature in or after May and increased precipitation throughout the growing season caused increased development of *M. graminicola.* Among cultivation treatments (Table 3.14), disease severity (logit transformed) in % leaf 1, % leaf 2, and % leaf 3 were significantly lower with CT than non-inversion tillage systems. There was no statistically significant undersowing or cultivation x undersowing effects on disease severity.

Table 3.14 *M. graminicola* severity under three tillage treatments (2012)

	% leaf 1	% leaf 2	% leaf 3
CT	-1.52b	-1.07b	-0.70b
LRNiT	-1.16ab	-0.85a	-0.48a
HRNiT	-0.97a	-0.79a	-0.36a
SED (10 df)	0.182*	0.089*	0.087*

*Values followed by the same letter do not differ significantly (*p <0.05)*

Sooty mould and Fusarium infected ears

Higher precipitations throughout the cropping year encouraged sooty mould and fusarium infections across the trial. Although, they were in low numbers, the number of ears (log transformation) infected with sooty mould (*Alternaria spp.* and/or *Cladosporium spp.*) and fusarium (*Fusarium avenaceum*) (Table 3.15) revealed that CT had significantly lower number of ear disease than non-inversion tillage systems. There was no significant undersowing or tillage x undersowing effects on ear disease severity.

Table 3.15 Ear disease severity under three tillage treatments (2012)

	Sooty mould ear (numbers m^{-2})	Fusarium ear (numbers m^{-2})
CT	0.295b	0.108b
LRNiT	0.639a	0.557a
HRNiT	0.660a	0.418a
SED (10 df)	0.145*	0.121*

*Values followed by the same letter do not differ significantly (*p <0.05)*

Gaeumannomyces graminis **var.** ***tritici***

Wet weather conditions throughout the cropping year and growing of second wheat led to the occurrence of take-all infection patches (Table 3.16). The experiment that comprised of 54 subplots, take-all patches were observed in 9 subplots (see Figure 3.1). The use of 0-3 index showed that HRNiT had higher infection patches followed by LRNiT, than CT. Among undersowing treatments, BM had higher take-all infection patches than WC or $N_{us.}$ Among cultivation x undersowing interaction, non-inversion tillage plots with BM undersown, showed some higher infection patches than WC.

Table 3.16 Take-all infection patches scored across husbandry treatments (2012)

Subplot number	Tillage	Undersowing	Index rate
20	CT	N_{us}	2
21	CT	BM	1
24	LRNiT	N_{us}	2
42	LRNiT	BM	1
54	LRNiT	WC	2
26	HRNiT	BM	3
44	HRNiT	BM	1
45	HRNiT	WC	2
47	HRNiT	BM	2

Plant heights and ear numbers

Among three cultivation treatments (Table 3.17), significantly taller wheat plants were found under CT followed by LRNiT, compared with HRNiT. Among undersowing, BM had significantly shorter wheat plants than $N_{us.}$ Similarly, at each time of assessment, ear numbers were significantly higher with CT followed by LRNiT, compared with HRNiT. Among undersowing, BM had significantly lower ear numbers, compared with $N_{us.}$ The mean values were therefore, reported (Table 3.17) for tillage and undersowing treatments. There was no statistically significant tillage x undersowing interaction on plant heights or ear numbers throughout the assessments.

Table 3.17 Plant heights and ear numbers under different husbandry treatments (2012)

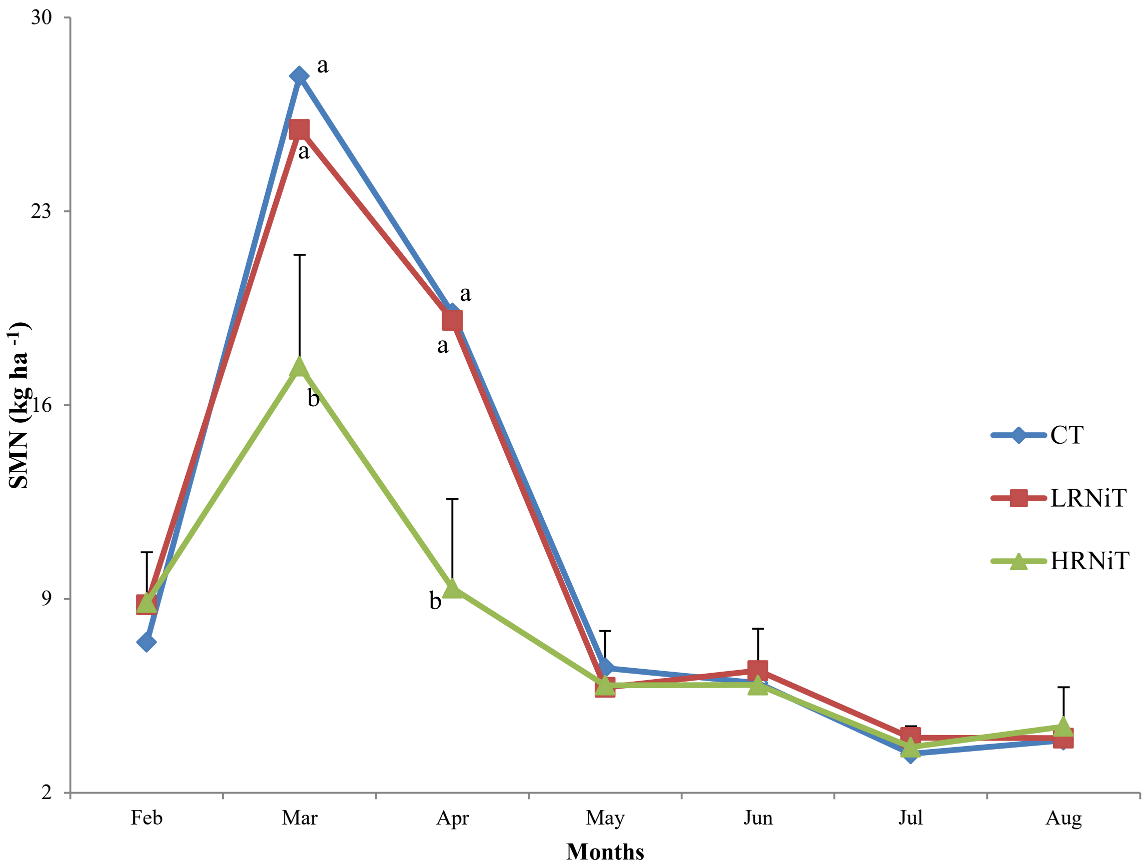
	Plant heights (cm)	Ear (numbers m^{-2}) (*mean values*)
CT	81.76a	350a
LRNiT	78.06b	274b
HRNiT	74.18c	217c
SED (10 df)	1.63*	19.31*
BM	76.10b	261b
N_{us}	79.76a	297a
WC	78.13ab	283ab
SED (30 df)	1.39*	10.93*

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05)*

Soil mineral nitrogen (SMN)

SMN assessed prior to cultivation (to provide base-line measurements) showed non-significant tillage effects. After cultivation (March) CT and LRNiT had significantly higher SMN, compared with HRNiT (Figure 3.3). This increased mineralisation rate was found until the following month (April). In later assessments (in and after May) there were no statistically significant tillage effects on SMN. This indicated that the increased mineralisation rates due to increased cultivations tend to decrease over time. Throughout the assessments, there was no statistically significant undersowing or tillage x undersowing effects on SMN.

Figure 3.3 Soil mineral nitrogen under three tillage treatments (2012) with error bars representing LSD (p<0.05) at each month

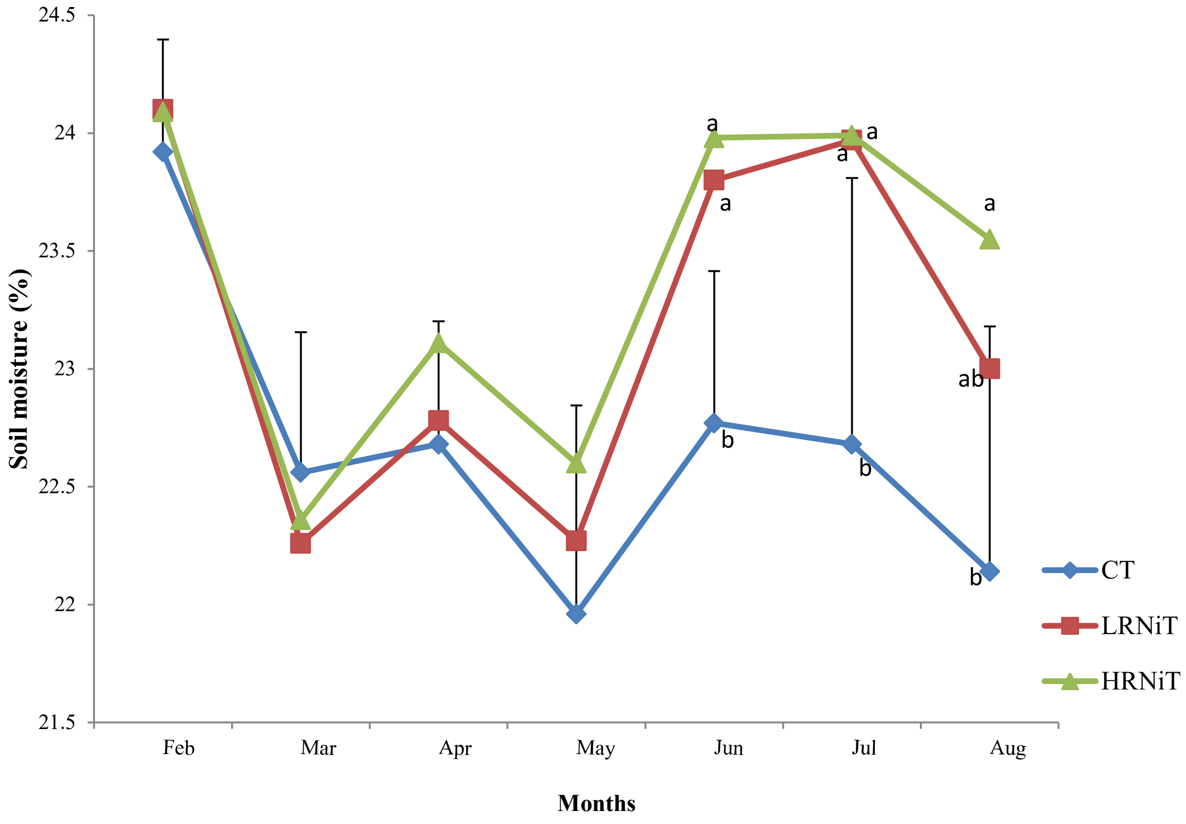


*Values at each month not sharing common letters differ significantly (*p <0.05, ns p >0.05).*
For each month, LSD is same for all the three treatments; hence HRNiT with error bar was only considered to represent at each month

Soil moisture status

Assessment in June, July and August 2012 (Figure 3.4), revealed that non-inversion tillage systems had significantly higher soil moisture percentage, compared with CT. This might possibly be due to the interaction of non-inversion tillage induced soil condition and influence of weather in particular, increased precipitation patterns (after June). Throughout the assessments, there was no statistically significant undersowing or tillage x undersowing effects on soil moisture percentage.

Figure 3.4 Soil moisture status under three tillage treatments (2012) with error bars representing LSD (p<0.05) at each month



*Values at each month not sharing common letters differ significantly (*p <0.05, ^{ns} p >0.05)*
For each month, LSD is same for all the three treatments; hence CT with error bar was only considered to represent at each month

Soil pH, P, K, organic carbon, total nitrogen, and earthworm numbers

Soil chemical parameters and earthworm numbers were evaluated mainly to characterise the seedbed conditions among different husbandry treatments. At each time of assessment, soil pH was significantly lower with non-inversion tillage systems, compared with CT. Soil organic carbon (C_{org}) and total nitrogen (N_t) (mostly in the organic form) was significantly lower with CT than non-inversion tillage systems. Earthworm population was significantly higher with HRNiT followed by LRNiT, compared with CT. The mean values were therefore, reported (Table 3.18). Throughout the assessments, there was no statistically significant undersowing or tillage x undersowing effects on soil chemical variables or earthworm numbers. At each time of assessment, although non-inversion tillage systems showed higher trend for soil P and

K, there was no enough evidence to trigger statistical difference, compared with conventional tillage. Irrespective of cultivation or undersowing treatments the soil P and K (grand mean) were 14.39mg l^{-1} and 213.10mg l^{-1} respectively.

Table 3.18 Soil chemical and biological characteristics for three cultivation treatments (*mean values* 2012)

	pH	% C_{org}	% N_t	Earthworm (numbers m^{-2})
CT	7.74a	2.39b	0.257b	65c
LRNiT	7.44b	2.57a	0.277a	106b
HRNiT	7.39b	2.65a	0.291a	141a
SED (10 df)	0.0372	0.061	0.007	13.33

*Values followed by the same letter do not differ significantly (*p <0.05)*

Final biological harvest

Final biological harvest results showed that CT had significantly greater DM of straw and ears, compared with LRNiT or HRNiT (Table 3.19). The 1000 grain weights and grain yield were significantly higher with CT, compared with LRNiT or HRNiT. Among undersowing treatments, N_{us} had significantly higher DM of ears and straw than BM. Grain yield and 1000 grain weights were significantly higher with N_{us} than BM. There was no statistically significant tillage or undersowing effects on estimated harvest index. Throughout the biological harvest assessment, there was no statistically significant tillage x undersowing effects on any of the tested variables.

Table 3.19 Wheat yield performance under different husbandry treatments (2012)

	Ears DM (t ha^{-1})	Straw DM (t ha^{-1})	Grain yield (t ha^{-1})	TGW (g)	Harvest index (%)
CT	4.36a	4.17a	3.52a	35.62a	41.52a
LRNiT	3.69b	3.60b	2.96b	33.98b	40.17a
HRNiT	2.68c	2.49c	2.11c	30.75c	42.28a
SED (10 df)	0.211*	0.226*	0.152*	0.72*	1.56 ^{ns}
BM	3.27b	3.14b	2.57b	31.95b	42.34a
N_{us}	3.89a	3.70a	3.13a	34.50a	40.62a
WC	3.59ab	3.41ab	2.89ab	33.90ab	41.02a
SED (30 df)	0.216*	0.178*	0.162*	1.02*	2.77 ^{ns}

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05, ^{ns}p >0.05)*

The difference in grain yield and straw DM among tillage and undersowing treatments affected a significant difference in total grain N uptake and hence total wheat N uptake (Table 3.20). Among tillage treatments, CT had significantly higher total grain N uptake and hence total wheat N uptake followed by LRNiT, compared with HRNiT. Among undersowing treatments, N_{us} and WC had significantly higher total grain N uptake and wheat N uptake than BM. There was statistically non-significant tillage or undersowing treatment effects on nitrogen harvest index or grain protein content.

Table 3.20 Wheat nitrogen yields under different husbandry treatments (2012)

	Total grain N uptake (kg ha^{-1})	Total wheat N uptake (kg ha^{-1})	Nitrogen harvest index (%)	Grain protein (%)
CT	68.1a	94.1a	75.81a	11.04a
LRNiT	55.6b	78.5b	74.58a	10.67a
HRNiT	39.6c	55.6c	73.95a	10.65a
SED (10 df)	3.36*	4.21*	0.762^{ns}	0.286^{ns}
BM	48.1b	67.9b	74.30a	10.58a
N_{us}	58.9a	82.5a	74.63a	10.72a
WC	56.3a	77.9a	75.41a	11.06a
SED (30 df)	3.28*	4.22*	0.668^{ns}	0.234^{ns}

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05, ^{ns}p >0.05)*

Among cultivation treatments (Table 3.21), legume DM and therefore total legume N uptake was significantly higher with non-inversion tillage systems than CT. Weeds DM and therefore total weeds N uptake were significantly higher with HRNiT than LRNiT or CT. Among undersowing treatments, legume DM and total legume N uptake was significantly higher when WC and BM were undersown than $N_{us.}$ Weeds DM and total weeds N uptake was significantly lower with WC than BM. Non-wheat DM yields and non-wheat N uptake were significantly higher with HRNiT than LRNiT or CT. Among undersowing, non-wheat DM yields were significantly higher with BM than $N_{us.}$ However, there was statistically non-significant difference in non-wheat N uptake among undersowing treatments.

Table 3.21 Legume and weeds biomass and their nitrogen yields under different husbandry treatments (2012)

	Legume DM (t ha^{-1}) (a)	Total legume N uptake (kg ha^{-1}) (c)	Total weeds DM (t ha^{-1}) (b)	Total weeds N uptake (kg ha^{-1}) (d)	Non-wheat DM (t ha^{-1}) (a)+(b)	Non-wheat N uptake (kg ha^{-1}) (c)+(d)
CT	0.250b	7.04b	0.337b	5.30b	0.587b	12.3b
LRNiT	0.643a	18.34a	0.644b	11.00b	1.287b	29.3b
HRNiT	0.793a	22.08a	1.938a	35.60a	2.731a	57.7a
SED (10 df)	0.087*	2.587*	0.385*	7.52*	0.407*	8.11*
BM	0.602a	16.76a	1.221a	21.1a	1.823a	37.9a
N_{us}	0.364b	10.46b	0.923ab	17.7ab	1.287b	28.1a
WC	0.720a	20.24a	0.775b	13.1b	1.495ab	33.3a
SED (30 df)	0.105*	3.028*	0.165*	2.99*	0.186*	4.86^{ns}

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05, ^{ns}p >0.05)*

3.4 Discussion for 2012 core experiment

Field condition prior to drilling – Overwinter 2011

In 2010/11 of winter wheat, irrespective of tillage treatments, the legumes were intercropped in the form of undersowing. Due to dry weather conditions, the establishment of legumes were greatly restricted during their growing period. However, non-inversion tillage systems had significantly higher legume DM, compared with CT. Similar trends were also observed during overwinter 2011. Tillage treatments also influenced weeds DM overwinter 2011, with CT and LRNiT having significantly lower weeds DM than HRNiT, as also seen in the 2010/11 winter wheat.

Among legume species undersown, throughout the cropping year 2010/11 of winter wheat, BM establishment was very slow, compared to WC. But, after the harvest of winter wheat, the legumes recovering overwinter 2011 exhibited considerable growth and biomass productivity. Nevertheless, WC had significantly higher legume DM than BM. Similar observation was also reported by Hartmann *et al.* (ca. 2009) that growth of black medic was characterised by low biomass yields, compared to white clover. The difference in biomass between WC and BM may have resulted in differences in their ability to compete with weeds. Among undersowing, weeds DM was significantly lower with WC, compared with BM or N_{us}. Similar observation was also reported by Doring *et al.* (2013) and Squire (1997) that BM showed no or lower competitive (reduced) effect on weeds, that would be expected from its biomass. The greater WC legume DM, which resulted in lower weeds DM, supports Hartwig & Ammon (2002) and Liebman & Dyck (1993) that the efficacy of cover crop in weeds suppression mainly depend on its biomass production. Against these conditions, core experiment 2012 with spring wheat was performed and the influence of various husbandry techniques was evaluated.

Effect of tillage treatments on soil penetration resistance

According to Carter *et al.* (1965); Wilhelm *et al.* (1982); Lopez-Bellido *et al.* (1996) tillage-induced seedbed conditions can exert direct effects on soil penetration resistance and indicate how easily roots can penetrate into the soil as a measure of plant growth. Higher penetration resistance reportedly reduce root growth and crop production (Gregory 1994; Taylor 1983). Among three cultivation treatments, the penetration resistance under HRNiT was significantly higher than CT or LRNiT at 5cm, 10cm, and 15cm soil depth (despite soil moisture content at different soil depth not being directly assessed). Similar observation was also reported by Ehlers *et al.* (1983); Wander & Bollero 1999; Pelegrin *et al.* (1990) that greater resistance of the soil to root penetration under conservation tillage, especially in the upper 0-10cm soil depth, due to more limited soil movements and greater presence of surface crop residues.

Locher & De Bakker (1990) reported that uninterrupted root growth can take place at penetration values below 1.5MPa (1500kPa). A value of greater than 2MPa can be regarded as the upper limit for uninterrupted root growth (Atwell 1993). Compared with these results, penetration resistance value although, was higher under HRNiT at each soil depth, the values were within levels that may not possibly restrict root growth and therefore crop production. In addition, some studies (Pietola 2005; Griffith *et al.* 1986; Koolstra & Boersma 1994) reports that it is not so unusual to detect greater soil resistance under reduced tilled soils. Despite, higher soil resistance, the crop production are usually unaffected, compared with conventional tillage (Lopez-Garrido *et al.* 2014). It is so because the root growth with conservation tillage was reportedly prompted by the presence of cracks, fissures, higher organic matter content in the top soil and increased worm channels as a result of greater biological activity (- which may not be detected by penetrometer), thereby compensating the absence of mechanical macropores introduced by the plough (Rasmussen 1999; Whalley *et al.* 1995).

Effect of tillage treatments on spring wheat yield performance

Levels of tillage intensity can alter seedbed conditions that can possibly affect plant establishment, crop growth and therefore crop yields (Strudley *et al.* 2008). Among multi-tooled cultivation treatments, seedbed conditions developed by maximum soil manipulation and complete burial of surface soil cover (CT) gave significantly higher plant establishment followed by minimal soil movements and 30% soil cover (LRNiT), compared with least soil movements and >50% soil cover (HRNiT). This observation reconfirms Siemens *et al.* (2004) and Wilkins *et al.* (1989) that the greater presence of soil cover due to less soil movements under non-inversion tillage systems may possibly interfere with the drill causing uneven seeding depth and poor seed-soil contact. This condition may have reduced plant establishment, compared to tilled seedbed. In addition, the existence of previous wheat stubbles under non-inversion tillage could also have negatively influenced crop establishment. Although, crop residues affect the growth of weeds (DeFrank & Putnam 1978), it has been reported that the mixed cereal straw residues can have a detrimental effect on the following crop establishment and early growth, because of phyto-toxicity (Rice 1984; Lovett & Jessop 1982; Alam 1990; Elliott *et al.* 1976). Nevertheless, greater presence of surface soil cover reportedly help prevent soil crusting, by protecting the surface from heavy rain drops as well as reduction of surface evaporation (Awadhwal & Thierstein 1985; Borresen 1990).

On an average tiller per plant under CT appear to be 1.2, LRNiT 1.1 and HRNiT 1.1 (LSD 0.213^{ns}) respectively. However, cultivation treatments that affected plant establishment also influenced the number of tillers, with CT having significantly higher tiller numbers followed by LRNiT, compared with HRNiT. According to Rasmussen *et al.* (1997) and Johnson & Lowery (1985) the continuous presence of soil cover under non-inversion tillage systems may alter topsoil characteristics, by reducing the rate of evaporation, and also limits fluctuation of soil temperatures. Consequently, these relatively cool soils could possibly slow onset of tillers, compared to conventional tillage. Such an impact was, however, not realised on total number of shoots, assessed twice. In each time of assessment, CT that had significantly higher number of plant establishment and tiller numbers resulted in significantly greater shoot density than non-inversion tillage systems.

Wheat DM throughout mid-season assessments (Phase I, II and III) varied among cultivation treatments. Generally, CT that had significantly higher plant populations also prompted significantly higher wheat DM than non-inversion tillage systems. Similar findings were also reported by Rieger *et al.* (2008); Acharya & Sharma (1994) that mouldboard ploughing produced significantly higher cereal mid-season biological yields, compared to conservation tillage due to reduced variability in seedbed conditions. Throughout the assessments, cultivation treatments had statistically non-significant effects on wheat nitrogen concentration. Similar observation was also reported by Iragavarapu & Randall (1995); Dou *et al.* (1994) and Lavado *et al.* (2001). Among tillage treatments, wheat N uptake to a larger extent was determined by wheat biomass. Accordingly, throughout the assessments, CT that had significantly higher wheat biomass also resulted in significantly higher wheat N uptake. However, regardless of cultivation treatments, the relationship between wheat N concentration and wheat DM were not always linear. At Phase I, wheat N concentration was higher and characteristically declined as the plant ages and accumulates dry matter. This non-linear relationship between wheat N concentration and wheat biomass appears to be general phenomenon, as reported by Tinker (1978); Greenwood (1982); Pearson & Muirhead (1984). Nevertheless, N% or wheat N uptake at various growth stages in particular, at/or after GS30 can be an possible indicator of grain protein content and grain yield, as described by Roth *et al.* (1989); Scharf *et al.* (1993) and Vaughan *et al.* (1990a).

Consistent crop field performance under conventional ploughing might be due to the reduced variability in seedbed conditions. According to Nielsen (2001) and Boomsma *et al.* (2010) several factors contribute to the potential variability in seedbed conditions, including variation in intensity of tillage practices, soil residue cover, weeds competition and environmental conditions. Nevertheless, conservation tillage systems often possess a greater number of these potential factors of variability in seedbed conditions at very early stages of crop growth (West *et al.* 1996; Boomsma *et al.* 2010; Nielsen 2001; Andrade & Abbate 2005; Liu *et al.* 2004). Similar observations were also realized in this study that the onset of variability in plant stand and crop growth under non-inversion tillage systems occurred very early in the growing season, due to the possible variation in seedbed conditions, compared with ploughing. Additionally, plant to plant variability (field observation) was also more pronounced within non-inversion tilled plots, compared with conventional tilled plots. Tillage related seedbed variability, therefore, may heighten the negative effects of crop field performance, according to Nielsen (2001), that when plant establishment is likely to be variable with conservation tillage, compared with conventional tillage, the crop growth also likely to vary, thereby reducing the overall yield.

Increased precipitation throughout the cropping year favoured the growth and establishment of the legumes. Among tillage treatments, legumes DM were significantly higher with non-inversion tillage systems, compared with conventional tillage at each time of assessment. This was due to recovery of residual legumes under non-inversion tillage systems to which wheat was oversown, along with annual addition of legumes by undersowing that contributed to the greater legumes DM.

Throughout the cropping season, HRNiT had significantly higher total weeds DM than CT or LRNiT. This trend reconfirms the previous observations in 2010/11 that at lower levels of tillage intensity there was a greater total weeds DM. Previous studies have reported that conventional ploughing is effective in providing initial weed-free environment (Pareja *et al.* 1985; Clements *et al.* 1996a). Similarly, in the present study increasing levels of tillage intensity with CT and LRNiT provided a lower weed environment when the main crop is establishing. This situation is very important in organic farming conditions, supporting Roberts & Feast (1972), because once the main crop is established with more limited competition and covers the ground it can exert greater competitive ability against later emerging weeds. However, this was not the case with HRNiT, because most of the weeds can potentially stay near or on the soil surface due to less soil movements without inversion, and the germination and emergence of weeds can be triggered under favourable conditions supporting Phillips *et al.* (1980); Clements *et al.* (1996a); Pareja & Staniforth (1985) and Swanton *et al.* (2000). Additionally, complexity in seedbed condition due to uneven seedbed and seed spacing; variability in crop growth under non-inversion tillage systems (particularly HRNiT) could also provide a more favourable environment for greater weeds emergence at early wheat growth stages.

Most of the weed species identified were commonly occurring weeds for spring wheat (HGCA 2010a) influenced more by crop type, environment, site location, and time of year, reinforcing Derksen *et al.* (1993). In comparison to 2010/11 of winter wheat, spring wheat in 2012 had an increase in dicotyledonous weed species. This may have been due to the higher rainfall after warm early spring favouring greater annual weed species emergence, as indicated by Teasdale (1998). Nevertheless, the type of cultivations practiced determined its species composition and biomass. Throughout the mid-season assessments, broadleaf weeds DM were significantly higher with CT, compared with HRNiT. Similar findings were reported by Froud-Williams *et al.* (1983b) and Locke *et al.* (2002) that increase in occurrence of broadleaf weed species with conventional compared to non-inversion tillage systems. Alexander & Schrag (2003) reported that many short-lived annual broadleaf weed species occurring in arable production are stimulated by soil disturbance under favourable conditions. However, the probability of germination of these species can greatly vary depending upon frequency, intensity and timing of soil disturbances (Froud-Williams *et al.* 1984). In addition, the possibilities of carryover of non-dormant buried weed seeds (although, soil weed seed bank was not being directly studied) might also have contributed to the increase in DM of broadleaf weeds under CT, supporting Froud-Williams *et al.* (1983b); Hakansson (2003) and Colbach *et al.* (2005). Throughout the growing season, grass weeds DM was significantly higher with HRNiT, compared with LRNiT or CT. This finding is in line with the findings of Locke *et al.* (2002) and Hakansson (2003). The ability of most grass weeds to survive at shallow emergence depth due to more limited soil movements without inversion could possibly allow greater re-vegetation, supporting Pareja & Staniforth (1985). Nevertheless, the reduction in broadleaf weeds DM under non-inversion tillage systems, in particular HRNiT, may also be due to the less soil movements that might have prevented tillage promoting weed germination, as described by Teasdale *et al.* (1991).

Overall, the biomass differences of broadleaf and grass weeds and therefore total weeds between CT and HRNiT was more pronounced. However, the difference between CT and LRNiT was not statistically significant. Even though the differences in total weeds DM and separated broadleaf and grass weeds DM between LRNiT and CT were quite large, the statistical test did not show any significant differences. This was due to the considerable variability of the data at each sampling time, possibly due to an increased complexity of seedbed condition (Siemens & Wilkins 2006) and uneven distribution of weed species (Froud-William *et al.* 1984). An indication of this is the ratio of the SED and the mean between CT and LRNiT, maybe the sampling area or number of replications could have been increased to overcome this variability. In general, this study shows a similar trend that increasing the levels of tillage intensity, results in a decrease in total weeds and grass weeds DM, as reported in other studies (Hakansson 2003; Clements *et al.* 1996a; Swanton *et al.* 2000; Froud-William *et al.* 1983b).

The 2012 cropping season with warm temperature in or after May and increased precipitation throughout the cropping season caused increased development of *M. graminicola* compared to winter wheat in 2010/11. This observation reinstates that the weather patterns (rainfall distribution) accounts for the greater differences in development of *M. graminicola,* supporting Smiley & Wilkins (1993). The higher development of *M. graminicola* resulted in statistically significant tillage effects on disease severity due to the possible differences in soil or seedbed conditions. Among three cultivation treatments, CT had significantly lower *M. graminicola* disease severity, compared with non-inversion tillage systems. The intensification of disease severity under non-inversion tillage may have been due to the increased susceptibility of the crop grown under non-inversion tillage and in addition, the difference in soil moisture status. The significantly higher soil moisture percentage in and after June under non-inversion tillage systems might possibly have altered the soil environment prompting cooler soil temperature, and also slow down warming and drying process due to the presence of greater soil cover, thereby increasing the disease severity, as the pathogen prefers wet and humid conditions (HGCA 2010b). Similar observation was also reported by Bockus & Shroyer (1998) and Rothrock (1992) that under high disease development situation, conservation tillage can have an greater impact on the types and severity of crop diseases mainly due to reduced soil movements and continuous presence of soil surface residues, which can possibly reduce evaporation and also lowers soil temperature, thus providing a more favourable environment for survival and distribution of pathogen inoculum, compared with conventional tillage.

The prolonged wet weather that coincided with wheat anthesis also resulted in the occurrence of sooty mould and fusarium, as the spores may have been splashed onto the ears and infects the developing grain. In this study, the occurrence of sooty mould was randomly distributed, while fusarium existed in patches. Among cultivation treatments, CT had significantly lower ear disease, compared with non-inversion tillage systems. The variation in seedbed condition under non-inversion tillage explains the intensification of disease severity. Generally, one of the objectives of non-inversion tillage is to conserve soil moisture (Derpsch *et al.* 2010). However, non-inversion tillage-induced seedbed condition in response to wet weather can have greater impact in magnifying the disease severity, compared with conventional tillage, supporting Bockus & Shroyer (1998) and Rothrock (1992).

Take-all, the major cause of second wheat syndrome (HGCA 2010b) was also observed. Growing conditions such as wet weather cycles, alkaline pH and limited nutrient levels are ideal for the spread of take-all patches, supporting Yarham (1981) who demonstrated that take-all is usually severe in the second successive cereal crop with the condition of wet years, puffy seedbed, poor drainage, soil pH neutral or alkaline, moisture is abundant and soils are deficient in nutrient levels especially nitrogen. In this study, non-inversion tillage had higher take-all patches. The difference in soil conditions and soil moisture levels might be the possible reason for increased take-all patches under non-inversion tillage, compared with conventional tillage.

Plant diseases are responsive to fluctuation in temperature and precipitation patterns (Turner 2008). According to Roget (2001) pathogenic organisms negatively affect plant growth and naturally exist in relatively low numbers in the soil. Under favourable soil and climatic conditions, disease outbreaks can be caused by an increase in population of the pathogens or likewise increased crop susceptibility to the pathogens. In this study, either reason may have accounted for the greater cause under non-inversion tillage, compared with conventional ploughing. Firstly, the wet weather conditions induced an increase in soil moisture status, which might have increased the population of pathogens in particular, under non-inversion tillage. Secondly, the increased predisposition of the crop under non-inversion tillage (in particular HRNiT) due to the greater variation in plant emergence and crop growth, and finally the existence of greater competition from weeds causing more vulnerability of primary crop. These observations, supports Nielsen *et al.* (2006) who reported that conservation tillage often increase plant to plant variability, this can lead to weakened plants that have to tolerate greater stress such as nutrient limitation, weeds competition and also compete with their healthier plants throughout the remainder of the growing season, which could also make them more vulnerable to diseases, compared with conventional tillage under high rainfall.

Overall, this study experienced unusual and contrasting weather patterns compared to the long term seasonal average. The climate change had exerted greater impact in influencing the crop performance and productivity in particular, with non-inversion tillage systems, intensifying the severity of diseases, and adding further complexity to the seedbed conditions, compared with conventional tillage. Unlike winter wheat in 2010/11, the increased disease severity (in particular, non-inversion tillage systems) had greater relevance to crop productivity because the infected crops produced shrivelled, discoloured, and lower grain weights.

Similar to 2010/11 winter wheat, in the present study, ear numbers were positively related to the cultivation-induced resultant effects on total number of shoots. Among three cultivation treatments, CT had significantly greater ear numbers and also taller plants than LRNiT or HRNiT. The 2012 of spring wheat that experienced higher precipitation resulted in cooler and wetter soil environments. Since non-inversion tillage systems often have a greater variability in seedbed conditions, the climate change may have further indirectly contributed to the complexity of the seedbed conditions inducing slower plant growth and shorter plant heights, regardless of weed pressure. These observations supports West *et al.* (1996) and Boomsma *et al.* (2010) who reported that seedbed conditions are more variable with conservation tillage. Implying that tillage related variability in response to environmental conditions can magnify negative effects of non-inversion tillage systems causing poor plant stand and lower crop heights, compared with conventional.

The cultivation treatments also affected DM of straw and ears, with CT being significantly higher followed by LRNiT, compared with HRNiT. Increase in TGW with

CT also resulted in greater grain yield, compared with LRNiT or HRNiT. Various factors including differences in agricultural management, weather conditions, weed competition, poor drainage, incidence, and severity of diseases have influenced crop growth and yield response between tillage treatments. The condition as with the present study; excessive precipitation, low soil temperatures, greater weeds competition, and disease pressure reportedly cause lower crop yield components and yield with conservation tillage relative to conventional ploughing (Griffith *et al.* 1977; Papendick & Miller 1977; Costamagna *et al.* 1982; Hargrove & Hardcastle 1984). Grain yield is the product of biomass at maturity, and the proportion of biomass that is partitioned to the grain (Martinez *et al.* 2008). The effect of tillage treatments has been seen on biomass production and the following yield. Difference in biomass among tillage treatments, therefore, could be a possible indicator of crop yield, re-confirming the view of Kumudini *et al.* (2008). Despite differences in total wheat DM, TGW and grain yield between tillage treatments, there was no significant difference in grain protein content. Although, the increase (or perhaps) excess soil moisture levels and greater weed infestations might have affected grain N % or grain protein content under non-inversion tillage systems. In general, the values obtained were statistically non-significant. This observation reinforces the previous findings of winter wheat in 2010/11, that tillage treatments had no effect on grain protein content, as compared to environmental and crop genotypic factors, as described by Terman *et al.* (1996); Robinson *et al.* (1979).

Effect of tillage treatments on soil mineral nitrogen (SMN)

Soil mineral nitrogen (NO_3-N and NH_4-N) for unfertilised crop is derived from the breakdown of crop residues or soil organic matter via the soil microbial biomass (Knight *et al.* 2008). Decomposition of these material can possibly release (mineralise) or lock up (immobilise) depending upon cropping environment (Knight *et al.* 2008).

After cultivation, CT and LRNiT had significantly higher SMN, compared with HRNiT. The increase in SMN with greater tillage intensity, compared to less soil movements, supports Douglas & Goss (1982); Blevins & Frye (1993) and Silgram & Shepherd (1999) who all reported that more tillage intensity increases soil nitrogen mineralisation through physical disturbance, exposing soil organic matter to greater micro-organisms that would release nitrogen from previously unexposed soil aggregates. Alvarez *et al.* (1995) reported that crop residues retained on soil surface due to less soil movements decompose slowly, and have greater N immobilization potential or lower rate of net N release than incorporated residues. The fact that the increase in SMN under CT and LRNiT, in comparison with HRNiT, was caused by an increase in NO_3-N (data not shown) serves as a proof of higher nitrification rates with increase in level of tillage intensity. Nevertheless, the effect of cultivation treatments on SMN was noticeable until April. Thereafter no statistically significant SMN differences were observed between tillage treatments. This supports Silgram & Shepherd (1999) and El Titi (2003) that increase in soil mineral nitrogen availability due to more mineralisation under increased cultivation often found to be moderately short-lived, although this depended much on the environmental conditions prevailing after cultivation.

Plant nitrogen uptake also depends on soil mineral N availability and root distribution (Gastal & Lemaire 2002). Knight *et al.* (2008) demonstrated that the amount of soil nitrogen likely to become available for crop N uptake is extremely variable and difficult to predict. According to Greenwood (1982), the N uptake rate of field crops is regulated not only by soil N availability but also crop growth rate. This is important because crop N uptake has often been considered in relation either to soil nitrogen availability (N supply approach) or to crop demand (N demand approach), rarely to both simultaneously (Greenwood *et al.* 1990). Rees *et al.* (1996) found a good relationship in spring cereals between the crop N uptake and the soil N using chemical extraction method with hot KCl (potassium chloride) solution. McTaggart & Smith (1993) found that the relationship between crop N uptake and SMN was often inconsistent on clay soils. The amount of SMN present might be greater or less than the measured value. This is always a possible source of error, because measurements of SMN are subject to considerable variation (Knight *et al.* 2008). Throughout the assessments, despite non-significant wheat N concentration among tillage treatments, wheat biomass and grain yield can be used as a possible indicator of nutrient uptake, as reported by Greenwood (1982). Accordingly, wheat under CT followed by LRNiT had significantly higher nutrient uptake, compared with HRNiT. Similar observation was also reported by Germon *et al.* (1994) that increase in soil disturbance, prompted greater nitrogen mineralisation, and also had better crop growth and productivity compared to less soil movements, despite nitrogen concentration was unaffected.

Generally, in comparison to utilisation of net SMN levels over time, wheat N uptake was variable among tillage treatments. This was due to the increased competition from non-wheat components (mainly weeds), in particular with HRNiT. The condition of transitory early nitrogen limitation, differences in plant population levels, and increased competition for nutrient uptake from non-wheat components with HRNiT might have contributed negatively on crop growth relative to other treatments. Irrespective of tillage treatments, soil mineralisation in clayey soil is often reported to be low due to a slow turnover of organic matter compared to other textured soils (Rasiah 1999) and with a cooler - wetter late spring and summer, might have affected mineralisation rates. This condition reflected that the crops took most of the N what was available, and potentially depleted soil nitrogen, thereby justifying the low values of SMN at later assessments under all tillage treatments.

Effect of tillage treatments on soil moisture status

Previous studies have reported that the possible effects of tillage practices on crop productivity in dry regions are attributed to the differences in soil moisture regimes (Chevalier & Chiha 1986; Lal 1982). Greater soil moisture content under conservation than conventional tillage has been widely reported (Whilhelm *et al.* 1989; Lal 1982). Triplett *et al.* (1968) reported that conventionally tilled soils although, might have higher initial water infiltration rate, this rate decreases rapidly due to surface sealing from rainfall. In contrast, the higher soil moisture content under conservation tillage have been reportedly attributed to numerous reasons including larger pores resulting in increased rainfall infiltration rate, less run-off and reduced evaporation from the soil surface due to the presence of crop residues (Jones *et al.* 1969; Bauder *et al*. 1981).

According to Flerchinger *et al.* (2003) if soil surface residues are incorporated by tillage, then they exert little effect on soil temperature. In contrast, continuous presence of living cover crops can substantially alter soil temperature. Beyaert *et al.* (2002) and Shinners *et al.* (1994) reported that the continuous presence of a flat and turf crop cover on the soil surface absorb less radiation, and were not efficient at trapping and retaining heat, compared to standing residue cover, and thereby slowing the soil warming process. Similarly, in this study, the continuous presence of widely distributed greater soil coverage of grass weeds and legumes under non-inversion tillage systems might be one of the possible reasons in heightening soil moisture levels. Additionally, irrespective of tillage treatments, the clay soil texture, under increased moist condition also behaved like plasticine - resistance to infiltration and thereby leading to water logging at later wheat growth stages (in/or after June). Nevertheless this condition was also more pronounced under non-inversion tillage systems. ADAS (2012) also reported that in southwest regions of UK continuous rainfall in June and early July had brought most soils to field capacity.

Generally, compared with conventional tillage, the soil moisture levels with non-inversion tillage systems was higher throughout the cropping year. However, in or after June, the soil moisture percentage was significantly higher with non-inversion tillage in response to wet weather, and also possibly of slow drying and warming tendency. This situation might have possibly affected the soil environment, and in turn caused crop production and increased the severity of diseases. Germon *et al*. (1994); Alvarez *et al*. (2001); Anken *et al*. (2004) also reported that under wet conditions and poorly drained soils, conservation tillage can affect crop growth and cause severe yield reduction by the existence of frequent anaerobic conditions due to increase soil moisture and cooler temperature. Higher soil moisture status with non-inversion tillage could be beneficial under dry conditions, but under wet conditions high (even excess) soil moisture status could be an important yield limiting factor causing various agronomic challenges with fields remaining wet for a longer time.

Effect of tillage treatments on soil chemical and biological properties

Soil chemical and biological assessment reflected the positive effects of non-inversion tillage systems, compared with CT. Several factors reportedly induce changes in soil reaction - including variation in tillage techniques, soil residue cover, weather events in particular rainfall distribution and crop type (Ismail *et al.* 1994). The soil pH values in general varied from 7.4 to 7.7, which is due to the calcareous parent material of the soil. Among three tillage treatments, soil pH was significantly lower with non-inversion tillage systems, compared with CT. This might possibly be due to increased moist soil condition, and also perhaps relatively greater organic matter on or near the soil surface by the continuous presence of soil cover causing reduced soil pH with non-inversion tillage (Blevins *et al.* 1977; Blevins *et al*. 1983a). Studies by Moschler *et al.* (1973) and White (1990) also observed lower soil pH under conservation tillage under high rainfall situation.

According to Bremner (1965) the concentration of total nitrogen (mostly in the organic form) in surface soils usually ranges between 0.08% and 0.4%. As a result, the values found in this study would be at moderate level consistent with moderate level of soil organic carbon under all tillage treatments. However, soil organic carbon and total nitrogen were significantly higher with non-inversion tillage systems, compared with CT. The relatively higher content of soil quality might be due to the less soil movements with continuous presence of soil cover that reportedly have potential to improve soil aggregates and accumulation of organic matter or redistributes organic matter to the soil profile (Blevins & Frye 1993), compared to frequent ploughing, that can reduce the amount of soil organic carbon by disrupting soil aggregation, and exposing organic matter to greater microbial activity, leading to its loss as carbon dioxide (Reeves 1997). Baker *et al.* (2007) also reported that non-inversion tillage showed a positive effect in soil organic carbon in the upper 30cm soil layer.

Reduction in soil tillage with higher availability of organic matter on the soil surface under non-inversion tillage systems also significantly increased earthworm numbers, compared with conventional ploughing. These results are similar to those reported by Edwards & Bohlen (1996); Francis & Knight (1993) and Karlen *et al.* (1994b) that greater the intensity and frequency of tillage lowers the population density of earthworms.

Effect of undersowing on spring wheat performance

The performance of undersown legumes under contrasting tillage treatments mainly relied on the competitive ability of legume to control weeds throughout the whole year, in particular, overwinter period. Undersown legumes that have grown during periods when main crop is not present (overwinter 2011), aided in maintaining ground cover and a niche that would may otherwise be occupied by weeds irrespective of tillage treatments, supporting Teasdale & Daughtry (1993) and Moyer *et al.* (2000). This condition is of great importance in particular, for non-inversion tillage systems as their residual effect continues due to oversowing of the 2012 spring wheat. The recovery of residual legume that covers the ground after 2012 spring wheat seeding may possibly be effective against early emerging weeds. However, they can also possess great competitiveness against the main crop, supporting Liebman & Davis (2009); Teasdale (1998) that the major limitation of oversowing cereals into the existing soil cover under conservation tillage is that their ability to compete with weeds will also compete with main crop, and thereby affecting primary crop growth and yield. Furthermore, the subsequent addition of undersowing to improve biomass production may also perhaps increase competition in a growing environment, due to greater competition for drawing potential resources such as light, nutrients, water and space, supporting Andersen *et al.* (2007); Enache & Ilnicki (1990). In contrast, conventional ploughing is an effective initial weed control tool. Undersowing legume shortly after drilling 2012 spring wheat was intended to withstand early competition from the main crop, and also compete with the later emerging weeds without coinciding with that of main crop, supporting Liebman & Staver (2001); Buhler *et al.* (2001) who reported that intercrops shortly after planting the main crop should establish more rapidly than weeds, and the peak period of growth coincide with that of other weed emergence but does not coincide with that of the primary crop. Nevertheless, Buhler *et al.* (2001); Fujii (1999) reported that complete suppression cannot be achieved by these techniques (use of legume intercrops either in reduced tillage or conventional tillage settings) because weeds can possibly escape suppression by cover crop due to morphological and physiological capabilities to access resources. Thus the intended function of undersowing and their effects on cropping environment potentially varied between tillage treatments.

To accrue the full benefits of undersown legumes (as above mentioned) in continuous organic cereal cropping, repeated annual undersowing was considered each year of the experiment. This made the assessment more difficult in comparing undersowing with non-inversion tillage systems against conventional tillage, because the competitive effect of the undersown legume and recovery or residual effects of previous undersown legume with non-inversion tillage systems were often confounded. Hence, the cumulative net effect of undersowing was therefore compared against non-undersown.

Teasdale *et al.* (1991) reported that interaction between tillage techniques and intercropping can influence crop growth, biomass accumulation, grain yield, weed populations, and species composition. However, this study showed that cultivation treatments had more prominent effects even before considering the effect of annual undersowing on crop growth, weed composition and its population density. This condition also further added to the complication of determining the actual performance of undersowing, irrespective of tillage treatments. An indication of this is the non-significant cultivation x undersowing interaction throughout the cropping year, despite developing distinct cultivation and undersowing effects.

The 2012 of spring wheat, increased precipitation favoured the growth, establishment, and dry matter production of legumes. Similar observations were also reported by Schroder *et al.* (1997); Bergkvist *et al.* (1995); Kankanen *et al.* (2001) that higher precipitation in spring and early summer correlated positively with cover crop biomass production. The occurrence of high rainfall throughout the cropping year after warm early spring also resulted in greater weeds competition. Teasdale (1998) reported that weeds competition can possibly begin earlier in a cropping cycles due to favourable conditions such as warmer temperature in spring followed by higher rainfall that may be advantageous for greater distribution of weed seeds. Among undersowing, although, there were statistically non-significant legume DM differences between WC and BM at Phase III and final biological harvest, the initial assessments (Phase I and II) showed that WC had significantly higher legume DM than BM or $N_{us.}$ This reinforces the previous results of winter wheat in 2010/11 that BM is less vigorous compared to WC at early crop development phase. A similar finding was also reported by Wallace (2001) that BM is slow to establish and not very competitive during early crop establishment phase. Although, BM may not be competitive at early main crop growth stages, the significant increase in total weeds DM under BM might have resulted in greater competition causing statistically significant lower wheat performance, compared with $N_{us.}$ Vyn *et al.* (1999) and Thorup-Kristensen *et al.* (2003) reported that a particular cover crop may suppress; have no effect or even allow multiplication of weeds based on its establishing ability relative to other weed emergence. Teasdale *et al.* (1991); Akemo *et al.* (2000); Wanic *et al.* (2005) also observed that a particular cover crop may reduce or increase the number of predominant species of short-lived weeds, which reveals complexity of effects of these practices on weed infestation. The greater above ground competition among crop species under spring wheat undersown with BM may have resulted in significantly lower total number of shoots, wheat DM and total wheat N uptake than N_{us}. These observations supports Crawley (1997) who reported that greater interspecific competition that occurred at the interface between crop species results in decrease of susceptible primary crop survival, growth and dry matter production.

In contrast, WC had significantly lower total weeds DM, compared with BM. This might be due to its ability to establish fast and cover the ground relative to other weeds emergence. Similar observation was also reported by Kwiecinska-Poppe *et al.* (2009) that white clover reduced the biomass of weeds in spring cereals. The positive ability of WC to compete with weeds than BM possibly reduced the negativity on spring wheat performance. This condition resulted in statistically non-significant total number of wheat shoots, wheat DM, and total wheat N uptake, in comparison with $N_{us.}$ Thus the ability of legumes to establish quicker may determine the success of cereal-legume intercropping. This observation supports Liebman & Dyck (1993) who indicated that the success of cereal-legume intercropping not only depends on the intercropped legumes complementing with the main crop but also on the infestations of weed population density. In addition, this study also indicates that complete weed control by legume cover crops probably cannot be achieved, supporting Teasdale (1996) who reported that complete weed suppression was never observed even with most competitive cover crop.

The increased crop-weed competition under spring wheat undersown with BM was also evidenced by stunted spring wheat heights and less ear numbers compared to $N_{us.}$ Although, spring wheat undersown with WC had shorter plant heights and lower ear numbers, they were statistically non-significant compared with N_{us}. Previous studies (Buhler *et al.* 2001; Ghaley *et al.* 2005; Ohlander *et al.* 1996; Solberg 1995) however, reports that the effectiveness of undersown crop in suppressing weeds is usually associated with reduced main crop performance, compared to monocultures.

Among the legume undersown, throughout the cropping year spring wheat undersown with WC significantly reduced dicotyledonous broadleaf weeds DM, compared with BM or $N_{us.}$ Similar observation was also reported by Clements & Donaldson (1997) that intercropping white clover resulted in limited occurrence of dicotyledonous weeds. The reason might be the quick establishment and dense canopy stand of white clover that have competed strongly with spring emerging dicot weeds (Facelli & Pickett 1991; Teasdale & Mohler 1993). Johnson *et al.* (1993); Teasdale *et al.* (1991) and Yenish *et al.* (1996) also reported a reduction in weed density and dry weight of early season annual dicotyledonous broadleaf weeds by clover cover crops. The slow establishment of BM and its reduced ability to compete with weeds, compared with WC resulted in higher dicotyledonous broadleaf weeds. Squire (1997) also observed no weed suppression by annual medics when inter-seeded into cereals. Throughout the cropping year, undersowing treatments had statistically non-significant effects on monocotyledon grass weeds DM, compared to non-undersown, WC though had lower values. This supports Clements & Donaldson (1997) that intercropping had no or a reduced effect on grass weeds.

Throughout the assessments, undersowing treatments had statistically non-significant effects on SMN. Vyn *et al.* (2000) and Lyngstad & Borresen (1996) reported that although, legumes fix atmospheric nitrogen they do not necessarily increase SMN. Undersowing legume treatments did not have any significant impact on *M. graminicola,* sooty mould, or fusarium. However, take-all patches were observed to be higher under BM than WC or $N_{us.}$ This observation was contrary to Lennartsson (1988) who reported a mixture of wheat and black medic reduced the incidence of take-all disease. The increased occurrence of take-all, in particular with BM, was confounded here, although, previous studies have reported beneficial and detrimental effects of intercropping on disease incidence, the effectiveness of disease attack often vary unpredictably in a cropping environment, supporting Trenbath (1993) and Risch (1983).

Final biological harvest result showed that despite statistically non-significant WC and BM legume DM, undersowing spring wheat with BM that resulted in greater weeds DM throughout the cropping year also led to higher non-wheat DM. This condition may have caused greater competition, lowering spring wheat yield associated components and grain yield significantly, in comparison with non-undersown spring wheat. Conversely, spring wheat undersown with WC did not show any statistically significant yield components or grain yield reduction, compared with non-undersown spring wheat.

This observation supports Gooding *et al.* (1993); Thompson *et al.* (1993b) that intercropping white clover in combination with wheat has potential for weed control, and also comparable yield advantages. Overall, this study finding in particular, with BM was contrary to the findings of Willey (1985); Hauggard-Nielsen *et al.* (2008) and Jensen (1996) however, showed similar trend to the findings of William & Hayes (1991); Koefoed (1996) and Clements *et al.* (1996b) that cereal-legume intercropping results in reduced yield components and fewer grain yields than wheat alone due to greater competition from legumes and weeds. Among undersowing treatments, there were statistically non-significant effects on grain protein content. This observation contradicts to the findings of Hauggaard-Nielsen *et al.* (2008); Reynolds *et al.* (1994) who reported that introducing a legume intercrop to cereal systems in organic or low-input environment increased grain protein content, compared to monoculture cereal. The success of cereal-legume intercrops on grain protein content (and grain yield) is therefore, highly variable depending on cropping environment, soil type, site location, and weather conditions, supporting Cavigelli *et al.* (2009) and Taylor *et al.* (2001).

3.5. Summary

Under the soil and weather condition which prevailed, spring wheat under CT with reduced seedbed variability and lower weeds burden resulted in significantly higher plant establishment, crop growth and final crop yields than other tillage treatments.

Weed competition is clearly a major limiting factor for organic crop production. Although the diversity of broadleaved weed species was quite large, considering the DM of weed species, grass weeds seems to be a major threat for adopting non-inversion tillage systems in organic farming. It could be regarded, perhaps, that some level of tillage is unavoidable to deal with grass weeds and therefore total weeds.

Increased rainfall throughout the growing season exerted a greater impact in influencing crop production and productivity than initially anticipated. The increased precipitation caused increase in soil moisture levels under non-inversion tillage. This condition intensified disease severity levels, and also increased seedbed complexity, compared with conventional tillage

The increase in soil organic carbon and nitrogen under non-inversion tillage is encouraging. The increase in earthworm population under non-inversion tillage systems also indicates that less soil movements with continuous presence of soil cover has the potential to improve earthworm density. The lowering of soil pH, in general, with non-inversion tillage systems under increased rainfall conditions needs to be monitored frequently, as soil acidification can hinder root growth, immobilise nutrients and may potentially reduce crop yields (Blevins *et al.* 1983b). Derpsch (2007) reported that the changes in soil properties by adoption of conservation tillage are often subjected to considerable variation in first two or three years. In the longer term, based on tillage activity, physical and chemical soil processes continually interact with time, resulting in diversely arranged mixture of soil minerals, organic matter, and pore spaces that together define soil structure (Blanco-Canqui *et al.* 2005). Hence, long term study and depth stratification is prudent to reconfirm soil characterisation.

Due to the nature and limitation of experimental design, the effects of legume cover crops on spring wheat growth could not be explained without considering the effect it exerted on weeds communities. The positive ability of quick growing WC that showed inverse relationship with broadleaf and total weeds possibly resulted in statistically comparable yield contributors and yield to that of N_{us}. In this context, WC seems to be a reliable legume cover crop option than BM.

Chapter – 4

CORE EXPERIMENT - III: PERFORMANCE OF ORGANIC SPRING WHEAT FOLLOWING DIFFERENT CULTIVATION SYSTEMS AND LEGUME UNDERSOWING

4.1 Introduction to 2013 core experiment

Following the harvest of 2012 spring wheat on 22 August 2012, the field was broadcasted with *Sinapis alba* (white mustard cv. Tilney) into existing soil cover, over the winter 2012. In the UK, mustard has been valued as a break crop between cereals (Holmes 1980). By including mustard as a part of crop rotation, pathogens in both soil and straw residue can be dramatically reduced (Haramoto & Gallandt 2004). Finnigan (1994) reported that wheat following mustard had significantly less sub-crown internode damage and crown blackening, caused by take-all disease. Wilson *et al.* (1994) described that when mustard was used as a part of crop rotation with wheat, the previous disease incidence decreased, and the yield increased from 17% to 20% compared to continuous cereal production (Ward *et al.* 1985; Almond *et al.* 1986; Grodzinsky 1992). Thus, by introducing mustard, it was thought that the disease severity levels from the previous cropping year could be possibly reduced, and grain yield could be improved. However, efficiency mainly depends on mustard growth and biomass production in a prevailing climatic condition. Against this background, the experiment was repeated with spring wheat cv. Paragon to reinforce the findings of 2012.

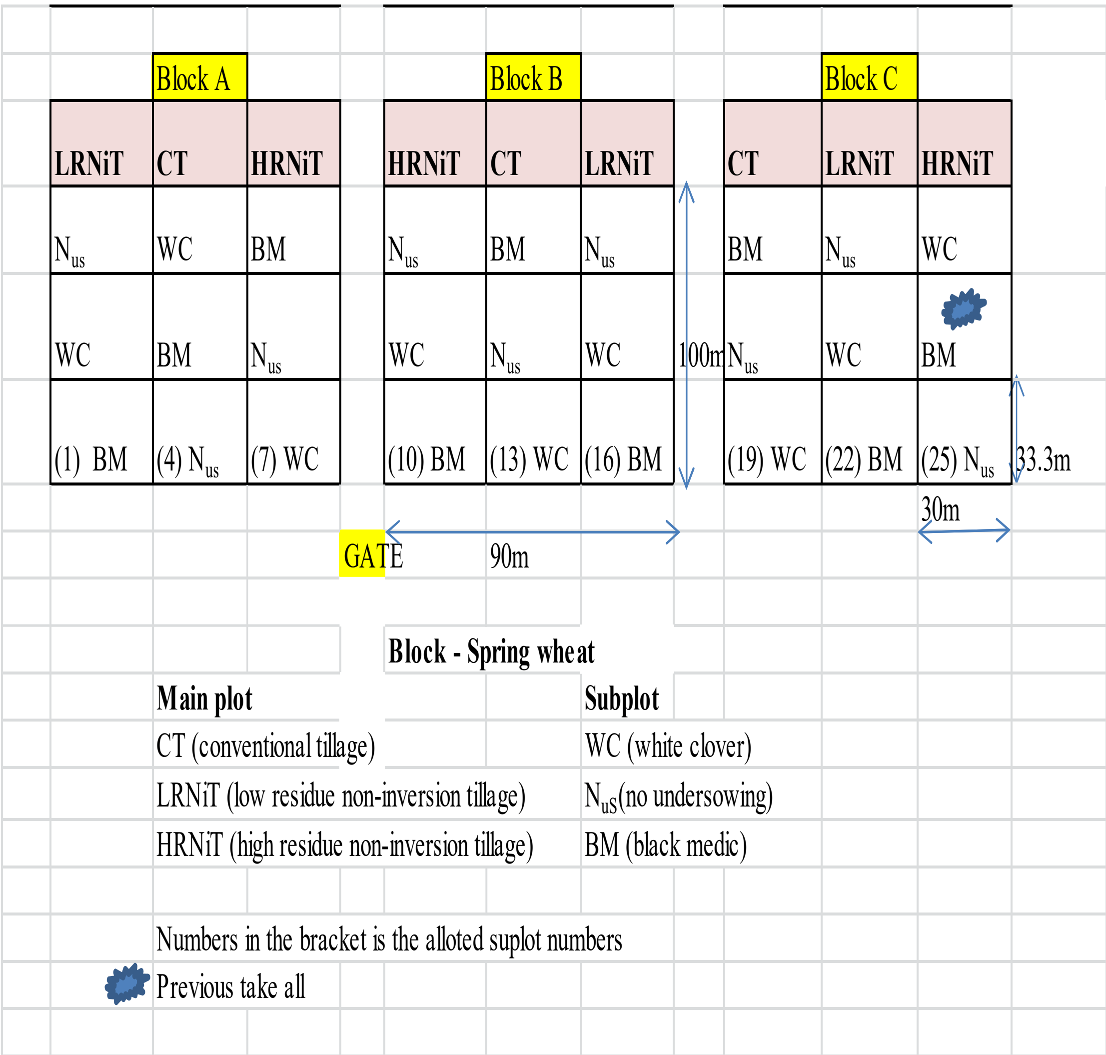
4.2 Materials and Methods for 2013 core experiment

4.2.1 Experimental design and treatment structure

The study was conducted from April 2013 to August 2013 on a field previously cropped with organic spring wheat cv. Paragon. The experimental design was the same as that described previously and using the existing experimental design structure (Chapter – 2, core experiment – I, §2.2.3). However, the experiment was restricted only to 2.7ha (3 blocks or 27 subplots) (see Figure 4.1), in comparison to the previous core experiments (winter wheat in 2010/11 and spring wheat in 2012). Three different (CT, LRNiT, and HRNiT) land preparation techniques were commenced after 20 March 2013, and spring wheat cv. Paragon at 420 seeds m^{-2} was planted on 10 April 2013. On 05 May 2013, undersowing treatments were established and the trial was harvested on 27 August 2013. The treatment structure (Figure 4.1) was a full factorial of:

Spring wheat (block) ***x*** *tillage systems (main plot)* ***x*** *+/- undersowing (subplot)*

Figure 4.1 Trial design for organic spring wheat 2013

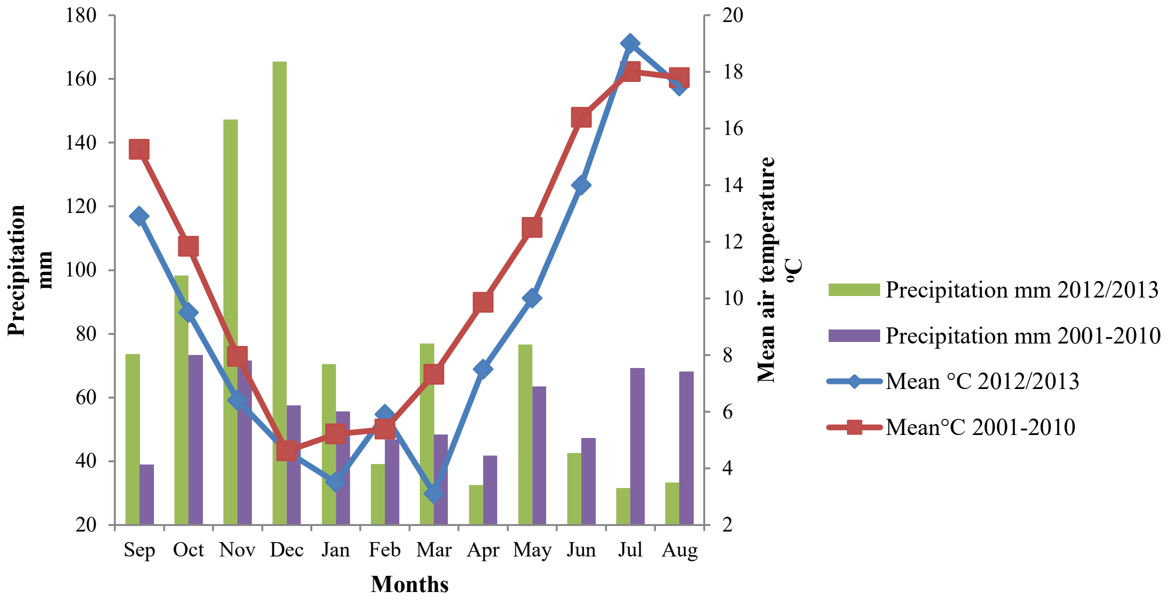


4.2.2 Meteorological conditions

The autumn and winter 2012 recorded an average air temperature of 7.1°C and precipitation of 594.1mm.

The 2013 cropping year (March to August 2013) recorded an average air temperature of 11.9°C and a precipitation of 292.2mm. During the cropping season the maximum and minimum air temperature was recorded in the month July (19°C) and March (3.1°C). Maximum and minimum rainfall received was in the month March (76.8mm) and July (31.5mm). The 2013 cropping year experienced higher precipitations in March and May and lower average air temperature throughout the spring and sudden rise in average air temperature in or after summer compared to long term seasonal average (Figure 4.2).

Figure 4.2 Mean air temperature and amount of precipitation during 2012/13 crop season. Royal Agricultural University Meteorological station, (NGR SP 42 004 011)



4.2.3 Assessments

Above ground assessments

2013 spring wheat above ground assessments (Table 4.1) conducted using the same protocol and formula as in Chapter – 2, core experiment – I, §2.2.4.

Table 4.1 Above ground assessments for spring wheat 2013

Assessments	Sample size	Date/Approximate growth stages
Legumes and total weeds biomass	0.25m^2 quadrat randomly with five replications per subplot	16 March 2013
Wheat establishment	0.25m^2 quadrat randomly with ten replications per subplot	07 May 2013
Number of wheat tillers	0.25m^2 quadrat randomly with ten replications per subplot	18 May 2013
Number of wheat shoots	0.25m^2 quadrat randomly with ten replications per subplot	05 June 2013
Growth assessments	Hand harvested randomly using a 0.25m^2 quadrat with five replications per subplot. Samples separated as wheat, legumes (white clover or black medic) and total weeds (specifically broadleaf or grass weeds, only at June and July)	Each month from the beginning of 25 May 2013
Wheat plant heights	Rising disk apparatus. Twenty random measures per subplot	01 August 2013
Number of wheat ears	0.25m^2 quadrat randomly with ten replications per subplot	10 August 2013
Final biological harvest	0.25m^2 quadrat randomly with five replications per subplot	27 August 2013

Soil assessments

2013 soil assessments (Table 4.2) conducted using the same protocol and formula as in Chapter -3 core experiment – II, §3.2.3.

Table 4.2 Soil assessments 2013

Assessments	Sample size/Date
Soil mineral nitrogen	Using Dutch auger core to a depth of 25cm, at twenty randomly selected positions within each subplot at monthly intervals beginning from 18 March 2013
Soil pH, organic carbon, total nitrogen, phosphorus and potassium	Air dried samples from each subplot after tillage (18 April 2013), during vegetation (18 June 2013) and before harvest (18 August 2013) from a depth of 0-25cm were analysed
Soil penetration resistance	5cm, 10cm, 15cm and 25cm soil depth using a hand penetrometer at ten randomly selected positions from each subplot after cultivation (05 May 2013)
Soil bulk density	0-5cm, 5-10cm, 10-15cm, 15-20cm, and 20-25cm soil depths using the core method. Two replications were randomly taken from each subplot after cultivation (05 May 2013) using a stainless steel core sampler of dimension 9.55cm diameter by 5cm height. The collected soil cores were trimmed to the exact volume of the cylinder, fresh weighed and oven dried at 105^oC for 24 hours. Soil dry bulk density was determined from the ratio of mass of oven dry soil per unit volume (358.36cm^3) of soil cores.
Earthworm numbers	Three replications per subplot after tillage (25 April 2013) and before harvest (20 August 2013).

4.2.4 Data analysis

Statistical analysis and reporting results, as stated in Chapter – 2, core experiment – I, §2.2.5.

4.3 Results for 2013 core experiment

Legume biomass and nitrogen accumulation overwinter 2012

Before cultivation, the overwinter assessment showed that there was no statistically significant tillage or undersowing treatment effects on legume DM and total legume N uptake (Table 4.3). The growth and biomass production of broadcasted mustard was highly restricted over the winter 2012 due to the increased competition from weeds.

Table 4.3 Legume biomass and nitrogen yields - overwinter 2012

	Legume DM ($t\ ha^{-1}$)	Total legume N uptake ($kg\ ha^{-1}$)
CT	0.211a	5.91a
LRNiT	0.270a	7.49a
HRNiT	0.166a	5.06a
SED (4 df)	0.046 ^{ns}	1.211 ^{ns}

Values followed by the same letter do not differ significantly (^{ns} $p > 0.05$)

Weeds biomass and nitrogen accumulation overwinter 2012

Before cultivation, the overwinter assessment showed that HRNiT had significantly higher weeds DM and total weeds N uptake than LRNiT or CT (Table 4.4). There was no significant undersowing or tillage x undersowing effects on weeds DM. The increased precipitation overwinter 2012 favoured increased growth and coverage of weeds, which substantially outcompeted the growth of undersown legumes, and also the establishment of broadcasted mustard.

Table 4.4 Weeds biomass and nitrogen yields - overwinter 2012

	Weeds DM ($t\ ha^{-1}$)	Total weeds N uptake ($kg\ ha^{-1}$)
CT	0.703b	16.8b
LRNiT	1.015b	24.1b
HRNiT	2.43a	59.0a
SED (4 df)	0.388*	7.11*

Values followed by the same letter do not differ significantly ($p < 0.05$)*

Soil bulk density

The soil bulk density measured after cultivation or during wheat emergence (05 May 2013) (Table 4.5) showed that CT and LRNiT had significantly lower soil bulk density than HRNiT at 0-5cm 5-10cm and 10-15cm soil depths. There were no statistically significant tillage effects on soil bulk density at 15-20cm and 20-25cm soil depths.

Table 4.5 Effect of tillage treatments on soil bulk density (2013)

	0-5cm	5-10cm	10-15cm	15-20cm	20-25cm
CT	1.29b	1.33b	1.24b	1.33a	1.47a
LRNiT	1.35b	1.39b	1.33b	1.29a	1.41a
HRNiT	1.48a	1.57a	1.46a	1.36a	1.49a
SED (4 df)	0.0346*	0.0594*	0.040*	0.055 ^{ns}	0.058 ^{ns}

*Bulk density (in gcm^{-3}) measured at early May at different soil depth. For each depth, values followed by the same letter do not differ significantly (*p <0.05, ^{ns} p >0.05)*

Soil penetration resistance

Soil penetration resistance measurement after cultivation or during wheat emergence (05 May 2013) (Table 4.6) showed that CT and LRNiT had significantly lower penetration resistance at 5cm, 10cm, and 15cm soil depth. There were no statistically significant tillage treatment effects on soil penetration resistance at 25cm soil depth.

Table 4.6 Effect of tillage treatments on soil penetration resistance (2013)

	5cm	10cm	15cm	25cm
CT	721b	934b	1291b	1508a
LRNiT	1027b	1161b	1358b	1498a
HRNiT	1945a	2135a	1858a	1811a
SED (4 df)	125.19*	100.74*	143.9*	115.6 ^{ns}

*Penetration resistance (in kPa) measured at early May at different soil depth. For each depth, values followed by the same letter do not differ significantly (*p <0.05, ^{ns} p >0.05)*

Plant establishment, tiller numbers, and total shoots

As in all the previous experiments, contrasting cultivation treatments significantly affected wheat plant establishment, with CT having significantly higher number of plants established followed by LRNiT, compared with HRNiT (Table 4.7). Contrasting cultivation treatments that affected plant establishment also influenced tiller numbers and total number of shoots, with CT having significantly higher number of tillers and total number of shoots than LRNiT or HRNiT.

Table 4.7 Wheat field performance under three tillage treatments (2013)

	Establishment (counts m^{-2})	Tiller (numbers m^{-2})	Total Shoot (numbers m^{-2})
CT	235a	270a	411a
LRNiT	178b	201b	312b
HRNiT	115c	132c	196c
SED (4 df)	10.15*	12.09*	30.70*

Values followed by the same letter do not differ significantly (p <0.05)*

Wheat biomass and nitrogen accumulation

During all the months of assessment (Table 4.8), wheat DM was significantly higher with CT followed by LRNiT, compared with HRNiT. The total wheat N uptake followed closely to that of wheat DM (Table 4.9). Throughout the assessments, there was no significant undersowing or cultivation x undersowing effects on wheat DM.

Table 4.8 Wheat biomass under three tillage treatments (2013)

	Wheat DM (t ha^{-1}) May	Wheat DM (t ha^{-1}) June	Wheat DM (t ha^{-1}) July
CT	0.360a	3.27a	4.66a
LRNiT	0.194b	2.53b	3.61b
HRNiT	0.064c	1.42c	1.99c
SED (4 df)	0.0418*	0.182*	0.184*

Values followed by the same letter do not differ significantly (p <0.05)*

Table 4.9 Wheat nitrogen yields under three tillage treatments (2013)

	Total wheat N uptake (kg ha^{-1}) May	Total wheat N uptake (kg ha^{-1}) June	Total wheat N uptake (kg ha^{-1}) July
CT	14.46a	37.84a	51.10a
LRNiT	7.69b	26.91b	37.21b
HRNiT	2.31c	15.42c	21.01c
SED (4 df)	1.605*	2.17*	1.88*

Values followed by the same letter do not differ significantly (p <0.05)*

Legume biomass and nitrogen accumulation

May assessment (Table 4.10) showed that non-inversion tillage had significantly higher legume DM than CT. However, in June, legume DM was significantly higher with LRNiT followed by HRNiT, compared with CT. But, in July, LRNiT had significantly higher legume DM than CT. Among undersowing treatments, May assessment showed non-significant differences in legume DM. However, in June and July, WC had significantly higher legume DM than BM or N_{us}. Throughout the assessments, there was no statistically significant tillage x undersowing effects on legume DM.

Table 4.10 Legume biomass under different husbandry treatments (2013)

	Legume DM ($t\ ha^{-1}$) May	Legume DM ($t\ ha^{-1}$) June	Legume DM ($t\ ha^{-1}$) July
CT	0.0098b	0.037c	0.067b
LRNiT	0.0747a	0.141a	0.195a
HRNiT	0.0618a	0.094b	0.132ab
SED (4 df)	0.0154*	0.0136*	0.0262*
BM	0.051a	0.085b	0.130b
N_{us}	0.030a	0.050c	0.095b
WC	0.065a	0.136a	0.168a
SED (12 df)	0.0164 ^{ns}	0.0143*	0.0159*

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05, ^{ns} p >0.05)*

In all the months of assessment, total legume N uptake (Table 4.11) among tillage treatments was similar to that of legume DM. However, among undersowing treatments, total legume N uptake varied, besides variation in legume DM. During May and June, total legume N uptake was similar to that of legume DM. However, in July, WC had significantly higher total legume N uptake followed by BM, compared with $N_{us.}$ The variation in N % (although statistically non-significant) in July might be the possible reason for the statistical variation in total legume N uptake.

Table 4.11 Legume nitrogen yields under different husbandry treatments (2013)

	Total legume N uptake (kg ha^{-1}) May	Total legume N uptake (kg ha^{-1}) June	Total legume N uptake (kg ha^{-1}) July
CT	0.33b	0.83c	1.44b
LRNiT	2.39a	3.20a	4.20a
HRNiT	1.94a	2.24b	2.85ab
SED (4 df)	0.530*	0.306*	0.539*
BM	1.49a	1.91b	2.77b
N_{us}	0.98a	1.14c	2.04c
WC	2.18a	3.21a	3.68a
SED (12 df)	0.554^{ns}	0.334*	0.324*

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05, ^{ns} p >0.05)*

Total weeds biomass and nitrogen accumulation

In May, HRNiT had significantly higher total weeds DM than LRNiT or CT (Table 4.12). However, in June, CT had significantly lower weeds DM than HRNiT. But, in July, there was no significant tillage effects on weeds DM. Throughout the assessments, there was no significant undersowing or tillage x undersowing effects on weeds DM.

Table 4.12 Total weeds biomass under three tillage treatments (2013)

	Weeds DM (t ha^{-1}) May	Weeds DM (t ha^{-1}) June	Weeds DM (t ha^{-1}) July
CT	0.259b	1.18b	1.55a
LRNiT	0.472b	1.54ab	1.98a
HRNiT	0.911a	2.51a	2.98a
SED (4 df)	0.090*	0.362*	0.568^{ns}

Values followed by the same letter do not differ significantly (p <0.05)*

During all the months of assessment, total weeds N uptake (Table 4.13) among tillage treatments varied besides variation in weeds DM. May assessment for total weeds N uptake were similar to weeds DM. However, in June and July, total weeds N uptake was statistically non-significant among tillage treatments. This might be due to the variability in N % or perhaps higher N % under CT and LRNiT than HRNiT (despite N% were statistically non-significant).

Table 4.13 Weeds nitrogen yields under three tillage treatments (2013)

	Total weeds N uptake ($kg\ ha^{-1}$) May	Total weeds N uptake ($kg\ ha^{-1}$) June	Total weeds N uptake ($kg\ ha^{-1}$) July
CT	7.71b	24.6a	30.6a
LRNiT	14.45b	33.2a	41.6a
HRNiT	29.38a	49.2a	56.3a
SED (4 df)	3.20*	8.93^{ns}	12.07^{ns}

Values followed by the same letter do not differ significantly ($p < 0.05$, ^{ns} $p > 0.05$)*

Weed species composition

Irrespective of cultivation or undersowing treatments, dominant broadleaf weeds were *Galium aparine* (Cleaver), *Taraxacum agg.* (Dandelion), *Rumex obtusifolius* (perennial dock), *Sinapis arvensis* (Charlock), *Sinapis alba* (white mustard), *Raphanus raphanistrum* (runch), *Lamium purpurem* (red dead nettle), *Fallopia convolvulus* (black bindweed), *Stellaria media* (chick weed), *Aethusa cynapium* (fools parsley), *Sonchus arvensis* (sow thistle), *Veronica persica* (field speedwell), *Chenopodium album* (fat hen), *Cirsium vulgare* (perennial spear thistle), *Viola arvensis* (field pansy), *Galeopsis tetrahit* (Hemp nettle), *Polygonum aviculare* (knot grass), *Geranium dissectum* (crane's-bill) and *Persicaria maculosa* (redshank). The dominant grass weeds were *Poa annua* (annual meadow grass), *Poa trivalis* (smooth and rough meadow grass), *Avena fatua* (wild oat), *Dactylis glomerata* (cocks foot), *Avena sativa* (oat), *Lolium perenne* (perennial rye grass), and *Phleum pratense* (timothy).

Assessment of weed species (Table 4.14) in June and July revealed that CT had significantly higher broadleaf weeds DM than HRNiT. Grass weeds DM in June were significantly higher with HRNiT than CT or LRNiT. But, in July, grass weeds were significantly higher with HRNiT than CT, while LRNiT was intermediate. In both the months of assessment, there were no statistically significant undersowing effects or tillage x undersowing interaction on weed species DM.

Table 4.14 Weed species biomass under three tillage treatments (2013)

	Broadleaf DM (t ha^{-1}) June	Grass DM (t ha^{-1}) June	Broadleaf DM (t ha^{-1}) July	Grass DM (t ha^{-1}) July
CT	0.977a	0.201b	1.25a	0.303b
LRNiT	0.615ab	0.929b	0.813ab	1.16ab
HRNiT	0.073b	2.438a	0.104b	2.87a
SED (4 df)	0.241*	0.265*	0.267*	0.69*

Values followed by the same letter do not differ significantly (p <0.05)*

Plant heights and ear numbers

Assessment of wheat plant heights and ear numbers (Table 4.15) revealed that CT had significantly taller wheat plants and higher number of ears followed by LRNiT, compared with HRNiT. There was no statistically significant undersowing or tillage x undersowing effects on plant heights or ear numbers

Table 4.15 Plant heights and ear numbers under three tillage treatments (2013)

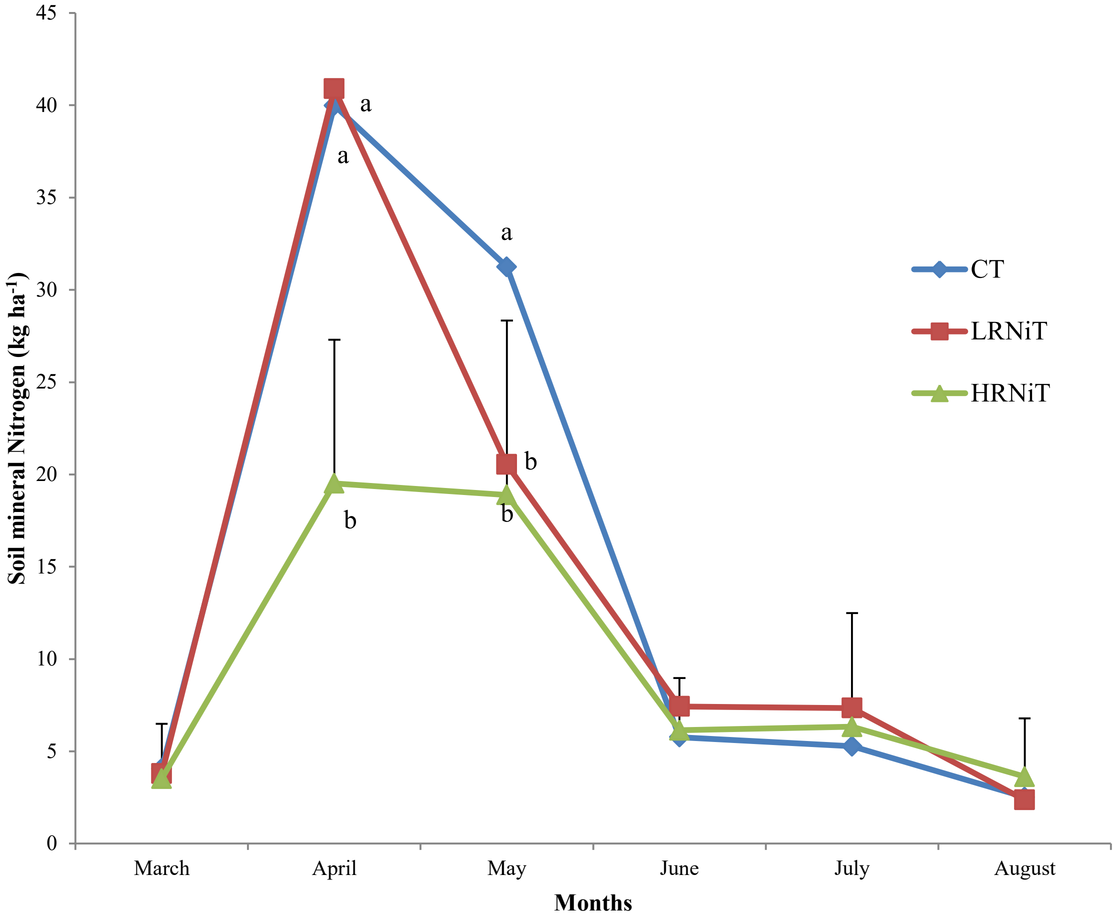
	Plant heights (cm)	Ear (numbers m^{-2})
CT	75.33a	277a
LRNiT	69.04b	211b
HRNiT	60.56c	121c
SED (4 df)	1.81*	15.70*

Values followed by the same letter do not differ significantly (p <0.05)*

Soil mineral nitrogen

Before cultivation, soil mineral nitrogen (SMN) (Figure 4.3) showed statistically non-significant tillage effects. After cultivation, CT and LRNiT had significantly higher SMN than HRNiT. This confirms previous observation in 2012 of spring wheat, that more tillage intensity increases mineralisation rate. However, in May, SMN was significantly higher under CT than non-inversion tillage systems. After May, there were statistically non-significant tillage effects on SMN. Throughout the assessments, there was statistically non-significant undersowing or tillage x undersowing effects on SMN.

Figure 4.3 Soil mineral nitrogen under three tillage treatments (2013) with error bars representing LSD (*p <0.05*) at each month



*Values at each month not sharing common letters differ significantly (*p <0.05, ns p >0.05)*
For each month, LSD is same for all the three treatments; hence HRNiT with error bar was only considered to represent at each month

Soil moisture status

At each month of assessment, although soil moisture percentage showed a higher trend under non-inversion tillage systems relative to CT, there was no statistically significant tillage effects observed. When assessed one month at a time, there is not enough evidence to trigger significance (SED's were too large). However, analysis with full data set (evidence of all the months into the test - mean soil moisture percentage, Repeated Measurements ANOVA) resulted in CT (20.29a) having significantly lower soil moisture levels than HRNiT (21.56b), while LRNiT found to be intermediate (21.11ab) (LSD (p <0.05) 0.866*). There was no statistically significant undersowing or tillage x undersowing effects on SMN.

Soil pH, P, K, organic carbon, total nitrogen, and earthworm numbers

At each time of assessments, although non-inversion tillage systems showed lower soil pH and higher soil P and K, there was no enough evidence to trigger statistical difference, compared with CT. Irrespective of cultivation or undersowing treatments the soil pH, P and K (grand mean as a result of Repeated Measurements ANOVA) were 7.6, 14.22mg l^{-1} and 211.01mg l^{-1} respectively.

Soil organic carbon (C_{org}), total nitrogen (N_t) and earthworm numbers were significantly higher with non-inversion tillage systems, compared with CT at each time of assessment. The mean value were therefore, reported (Table 4.16). Throughout the assessment, there was no statistically significant undersowing or tillage x undersowing effects on soil C_{org} or N_t or earthworm numbers.

Table 4.16 Soil chemical and biological characteristics for three cultivation treatments (*mean values* 2013)

	% C_{org}	% N_t	Earthworm (numbers m^{-2})
CT	2.37b	0.250b	46c
LRNiT	2.59a	0.287a	78b
HRNiT	2.70a	0.309a	106a
SED (4 df)	0.057*	0.012*	7.92*

Values followed by the same letter do not differ significantly ($p < 0.05$)*

Final biological harvest

Final biological harvest results (Table 4.17) showed that wheat ears and straw DM was significantly higher with CT followed by LRNiT, compared with HRNiT. The TGW and the grain yields were significantly higher with CT than LRNiT or HRNiT.

Among tillage treatments, total grain N uptake, and hence total wheat N uptake followed closely to that of grain yield and straw DM (Table 4.18). There were statistically non-significant tillage effects on estimated harvest index, nitrogen harvest index and grain protein content. Throughout the assessment, there were no statistically significant undersowing effects or tillage x undersowing interaction on wheat yield components or grain yield.

Table 4.17 Wheat yield performance under different husbandry treatments (2013)

	Ears DM (t ha^{-1})	Straw DM (t ha^{-1})	Grain yield (t ha^{-1})	TGW (g)	Harvest index (%)
CT	3.86a	2.77a	3.10a	30.84a	46.80a
LRNiT	2.79b	2.05b	2.22b	28.65b	45.00a
HRNiT	1.67c	1.07c	1.33c	25.51c	48.47a
SED (4 df)	0.260*	0.150*	0.226*	0.738*	3.05^{ns}
BM	2.72a	1.96a	2.16a	28.03a	45.94a
N_{us}	2.64a	1.86a	2.11a	28.07a	46.86a
WC	2.96a	2.06a	2.38a	28.94a	47.47a
SED (12 df)	0.234^{ns}	0.188^{ns}	0.180^{ns}	0.994^{ns}	0.891^{ns}

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05, ^{ns}p >0.05)*

Table 4.18 Wheat nitrogen yields under different husbandry treatments (2013)

	Total grain N uptake (kg ha^{-1})	Total wheat N uptake (kg ha^{-1})	Nitrogen harvest index (%)	Grain protein (%)
CT	61.2a	70.5a	85.38a	11.27a
LRNiT	43.6b	50.9b	84.46a	11.19a
HRNiT	25.8c	29.4c	85.41a	11.17a
SED (4 df)	5.28*	5.64*	0.803^{ns}	0.317^{ns}
BM	40.7a	47.4a	84.57a	10.89a
N_{us}	41.5a	47.8a	85.30a	11.21a
WC	48.4a	55.6a	85.39a	11.54a
SED (12 df)	4.11^{ns}	4.89^{ns}	0.736^{ns}	0.365^{ns}

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05, ^{ns}p >0.05)*

Among cultivation treatments (Table 4.19), legume DM and hence the total legume N uptake was significantly higher with LRNiT, compared with CT. Although, total weeds DM were significantly higher under HRNiT than LRNiT or CT, there was no significant difference observed on total weeds N uptake between tillage treatments. Among undersowing, legume DM and the total legume N uptake was significantly higher with WC than BM or $N_{us.}$ There was no suppressive influence observed among undersowing or tillage x undersowing interaction on weeds DM.

Table 4.19 Legume and weeds biomass and their nitrogen yields under different husbandry treatments (2013)

	Legume DM (t ha^{-1})	Total legume N uptake (kg ha^{-1})	Total weeds DM (t ha^{-1})	Total weeds N uptake (kg ha^{-1})
CT	0.076b	1.68b	1.88b	43.4a
LRNiT	0.233a	5.06a	2.46b	55.8a
HRNiT	0.162ab	3.54ab	3.57a	73.5a
SED (4 df)	0.0316*	0.710*	0.357*	10.89^{ns}
BM	0.138b	2.96b	2.81a	62.1a
N_{us}	0.123b	2.71b	2.66a	57.6a
WC	0.207a	4.62a	2.45a	53.1a
SED (12 df)	0.0156*	0.314*	0.395^{ns}	13.06^{ns}

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05, ^{ns} p >0.05)*

4.4 Discussion for 2013 core experiment

The broadcasted mustard appears to be completely outcompeted by the vigorous growth of weeds overwinter 2012. After the harvest of 2012 spring wheat, despite higher weeds prevalence (relative to the values at 2012 spring wheat final biological harvest), the increased rainfall during autumn and overwinter 2012 favoured greater growth and ground coverage of weeds under all tillage treatments. These weedy conditions adversely affected the growth of legumes and also limited the reliance of broadcasted mustard. There was no statistically significant tillage or undersowing effects, however, on legume DM overwinter 2012. Relative to weeds DM, among tillage treatments, HRNiT had significantly higher weeds DM than LRNiT or CT. This observation on weeds DM showed a similar trend to that of overwinter 2011. Against these conditions, experiment 2013 spring wheat was conducted and the effects of different husbandry techniques were assessed.

Effect of tillage treatments on soil bulk density and penetration resistance

Soil bulk density and penetration resistance was assessed mainly to recognise the impact of contrasting tillage treatments on seedbed conditions. These physical parameters will help to indicate soil's strength and thus resistance to plants as they penetrate the soil (Brady & Weil 1999). In this study, the soil water content on percent volumetric basis (data not shown) at different soil depth was not significantly influenced by tillage treatments and it is reasonable to assume that the differences in soil physical parameters are not the result of differences in soil water content. The effect of cultivation treatments (after cultivation or during wheat emergence) on soil bulk density and penetration resistance showed that more tillage intensity with CT and LRNiT had significantly lower soil bulk density (0-5cm, 5-10cm, and 10-15cm) and penetration resistance (5cm 10cm and 15cm) than HRNiT. Similar observation was also reported by Ozpinar & Çay (2005); McVay *et al.* (2006); Grant & Lafond (1993); Unger & Jones (1998); Franzluebbers *et al*. (1995) and Tebrugge & During (1999).

USDA (2008) reported that for clay soils ideal bulk density is <1.1gcm^{-3} and bulk density >1.47gcm^{-3} can hinder root growth. Similarly, Atwell (1993) reported that uninterrupted cereal root growth can take place at penetration values below 2MPa (2000kPa). Compared with these results, values of HRNiT at each soil depth were either closely correlated or exceeding the upper limit, that can possibly restrict root growth and therefore, harmful for crop production. Previous studies (Tisdall 1996; Radford *et al.* 2001) also indicated that greater soil resistance (≥1.47gcm^{-3} or ≥2MPa) mainly in the top soil, early in the growing season severely restricts crop production because crop stand must be established sooner after planting, with roots colonizing as early as possible and leaf area expanding rapidly if productivity is to be higher. Although, some studies (Gregory 1994; Bengough 1991) reports that the penetrometer values are 2 to 8 times greater than the resistance value that roots actually get while penetrating the soil. In the present study, the greater penetration resistance values were justified with the greater bulk density assessed on the same time. Generally, increase in soil physical parameters (compared to 2012 core experiment) under all tillage treatments might possibly be due to the preparation of seedbed under wet soil conditions (unexpected rainfall in late March). Soehne (1958) reported that the heavy farm equipment including tractors can exert considerable weight on the soil surface and the effect of equipment weight can penetrate down to 60cm when soils are moist and thus increasing the chance of temporal compaction.

Effect of tillage treatments on crop performance

The varietal choice, seeding rate, and drilling depth were similar to core experiment 2012. But, the drilling date was delayed compared to 2012, due to unusually higher precipitation in March 2013. Similar to the previous core experiments, as expected, the different cultivation treatments substantially influenced seedbed condition causing variation in plant establishment, with CT having significantly higher plant establishment followed by LRNiT, compared with HRNiT. As with 2012 spring wheat, the retention of previous wheat stubbles may also have negatively contributed to the crop establishment under non-inversion tillage systems (by phytotoxic effects), compared to conventional tillage. Nevertheless, irrespective of tillage treatments, the average establishment percentage of 42% was low compared to the previous 2012 of spring wheat. This might be due to the soil physical environment (greater soil physical variables) and also perhaps, later sowing on 10 April 2013.

As with previous core experiments, contrasting cultivation treatments had no significant influence on tillering. On an average tiller per plant under CT was 1.2, LRNiT 1.2 and HRNiT 1.2 (LSD 0.519^{ns}) respectively. Nevertheless, cultivation treatments that determined plant establishment in a growing environment also influenced tiller numbers and total number of shoots. Among tillage treatments, the greatest plant establishment with CT resulted in higher tiller numbers and total shoots, compared with other cultivation treatments. These observations were very similar to the findings in 2012 of spring wheat, reconfirming that for lower tillering organic spring wheat, the tillers numbers and total shoots are the resultant effect of contrasting tillage treatments on plant establishment.

Previous studies have reported that one of the phytotoxic symptoms of affected plants include reduced tillering (Elliot *et al.* 1976). In both the cropping years (2012 and the present study - 2013) tillering has not been significantly influenced by the type of residue retained, rather substantially determined by the number of plant established. This observation suggests that the ecosystem of non-inversion tillage is more complex, compared with conventional. How and when the surface retained residue release phytotoxins to the soil and its associated effects, and also the decomposition rates between incorporated residues and surface retained straw residues that influence the phytotoxicity is unclear (despite, not being directly studied). Although, Lyon *et al.* (2004) reports that much of the research on phytotoxic effects has been laboratory-based rather than examining in the field. Studies by Harper (1989) propose that even shallow incorporation of mixed straw residues will potentially reduce the adverse effect of phytotoxins on seedling growth. Nevertheless, assuming drill performance or seed-soil contact (which is more relevant to the study, regardless of soil physical environment) has a critical hindrance, removing crop residues from the seedling row under non-inversion tillage systems might potentially improve seedling emergence and therefore number of tillers, and also perhaps, limits the adverse effect of phytotoxins on seedling growth.

During all the months of assessments, wheat DM was significantly higher under conventional tillage than non-inversion tillage systems. This may be due to the possible difference in plant populations, a direct and resultant effect of seedbed conditions created by contrasting tillage treatments. However, in comparison to 2012 of spring wheat, the biomass production of wheat was relatively low under all tillage treatments. This might be possibly due to delayed sowing and greater crop-weed competition right from the early crop growth stages until harvest. Taylor *et al.* (2001) also reported that weeds are the overriding threat in over half the cereal crops grown under continuous stockless organic farming conditions. Initial biomass assessment showed that total weeds DM was half of the biomass accumulated by wheat under CT. For non-inversion tillage systems, the total weeds DM were very higher compared to wheat DM. This condition explains the severity of infestation and competitiveness of weeds relative to primary crop, adversely affecting main crop growth potential among tillage treatments in particular, the non-inversion tillage systems. Although, wheat DM increased at later stages under CT and LRNiT, HRNiT at each stage of assessment, had lower wheat DM relative to total weeds DM. Fodor & Palmai (2008) also found that wheat produced less biomass after late sowing, while that of weeds was greater.

As expected, the occurrence of weeds was more influenced by weather condition, crop type, and time of year. However, in contrast to previous experiments (2010/11 and 2012) where the total weeds DM were significantly higher throughout the growing season under HRNiT relative to CT or LRNiT, in this study, more variation was encountered at each sampling times. This might be due to the variation in seedbed condition, and increased weed prevalence, and more uneven distribution of weed species. Although, initial (May) assessment showed that increasing tillage intensity with CT and LRNiT had significantly lower total weeds DM than HRNiT, in June, CT had significantly lower total weeds DM than HRNiT, while LRNiT found to be intermediate. But, in July there was statistically non-significant difference in total weeds DM among tillage treatments. These differences might be due to the greater occurrence of weeds DM under CT and LRNiT. In general, increase in total weeds DM under all cultivation treatments (and also poor competitive ability of primary crop) have negatively impacted on crop production, as demonstrated by Bulson *et al.* (1996).

Similar to the previous core experiments (2010/11 and 2012); the occurrence of annual broadleaved weeds was significantly higher under CT than HRNiT, throughout the growing season. This observation reconfirms that, the more often the soil is cultivated, higher is the percentage emergence of annual broadleaf weed species in the weed community, supporting Holzner (1982). Throughout the growing season, grass weeds were significantly higher under HRNiT than CT as also seen in 2010/11 and 2012 core experiments.

Similar to 2012 spring wheat, the biomass differences of separated broadleaf and grass weeds, and hence total weeds between CT and HRNiT were more pronounced. However, the difference between CT and LRNiT was not statistically significant. Although, the differences in separated grass weeds DM between LRNiT and CT were quite large; the statistical test did not show any significant differences. An indication of this is the ratio of the SED and the mean between CT and LRNiT. Further experiments therefore, are required to clarify weeds severity between LRNiT and CT. Overall, compared to previous core experiments (2010/11 and 2012) where the broadleaved weeds had somewhat less relevance in terms of production, to that of grass weeds, the present study showed that frequent ploughing can substantially increase broadleaf weeds, which can also restrict organic crop production. Generally, the increase in weed population in each year and failure in controlling under all tillage treatments relative to uncertain climatic conditions proved to be a major competition in 2013 spring wheat cropping. This situation indicates the importance of additional or alternative weed control measures for sustaining organic crop production. This study further implies that cropping sequence, tillage techniques, and legume cover crops may probably not be only reliable option to deal with weeds over longer term organic cropping situation. This is because weeds stand better chances due to their vast genetic diversity and wider adaptability under varying environmental conditions, as seen in this study, and also reported elsewhere by Teasdale (1996).

Less rain from May and greater weeds competition not only affected the recovery of residual legumes, but also restricted the growth of annual addition of undersown legumes. Furthermore, undersowing into the emerged stand where primary crop competition is restricted due to vigorous growth of weeds also reduce the reliability of legumes to compete with weeds. Brandsaeter & Netland (1999) reported that for effective weed suppression the intercrop should grow fast and cover the ground until the main crop can prevent weed germination. This was not the case in the present study, as weed emergence and growth were overriding the primary crop ground cover throughout, in particular, under non-inversion tillage such as HRNiT. The distribution of legumes in a growing environment varied throughout the assessments. This might possibly be due to the uneven emergence of legumes across the trial, as a result of greater inter-specific competition. Among undersowing, initial assessment did not show any significant differences on legume DM. However, in June, July and final biological harvest, WC legume DM was significantly higher than BM. This observation reconfirms previous experiment findings (2010/11 and 2012) that WC establishment was more vigorous than BM, despite the existence of greater weed pressure.

Disease incidence was low (and not measured, as there were not sufficient levels to conduct an assessment) due to dry weather. However, the impact of previous take-all infection patches was visually witnessed on the present crop, in particular under HRNiT (subplot 26). This might be due to the less soil movements without inversion that resulted in retaining previous infected residues on or near the soil surface, as reported by Bockus & Shroyer (1998) and Sturz *et al.* (1997). Compared to other HRNiT subplots, subplot 26 (at far end from the gate, see Figure 4.1) approximately 25-30% of the subplot area had more stunted crop heights and white ear heads.

Cultivation treatments substantially influenced plant heights. Among three tillage treatments, CT produced significantly taller plants followed by LRNiT, compared with HRNiT. The variability in plant heights between cultivation treatments might be explained by the direct influence of tillage related management practices on seedbed condition, and possibly crop-weed competition. Average plant heights were relatively short compared to the cropping year 2012 under all tillage treatments. Differences in plant heights between the cropping years might be due to the more stressed seedbed environment, greater weeds prevalence, and also duration stress caused by delayed sowing. Young *et al.* (2004) and Prasad *et al*. (2008) reported that late sown crops are highly affected by stress, as they attempt to survive and complete all the developmental stages within a shorter period of time.

Among three cultivation treatments, the greatest total number of shoots developed with CT gave significantly higher number of ears, ears DM, straw DM, and grain yield followed by LRNiT, compared with HRNiT. Similar to previous study of spring wheat in 2012, contrasting tillage treatments that affected above mentioned variables also influenced TGW. However, the TGW in the present study was considerably lower, compared to 2012 of spring wheat under all tillage treatments. Differences in TGW between 2012 and 2013 cropping years might be due to the greater stress habitat condition and also perhaps sudden rise in average air temperature during grain filling stage in 2013, which might have lowered grain size and grain weights. Previous studies (Wheeler *et al.* 1996; Wardlaw *et al.* 1989; Midmore *et al.* 1994) have also reported that the late sown cereal experiencing a sudden rise in temperature during grain filling stage might results in lower grain size, grain weights, and grain yield with lower total plant biomass.

In general, although, thousand grain weights are reported to be genetically determined (Mogensen *et al.* 1985), in all core experiments (2010/11, 2012 and the present study), the expression of thousand grain weights appear to be strongly influenced by the interaction of cropping environment induced by contrasting cultivations and weather events. This supports Norwood (2000); Convertini *et al.* (1996); Lopez-Bellido *et al.* (1998); De Vita *et al.* (2007) that under stressed habitat and inadequate phytosanitary environment (relative to weeds or diseases) wheat grain is often characterised by smaller grain size and lower grain weights.

All core experiments (2010/11, 2012 and the present study) therefore, have indicated a positive relationship between wheat grain yield and yield component traits such as plant establishment, shoot numbers, dry matter production, plant heights, ears per unit area and thousand grain weights. The variation of these yield contributors caused by differences in seedbed conditions has helped clarify the expression of growth condition provided, supporting Fischer (1985); Ghaderi *et al.* (2009); Kandic *et al.* (2009).

Similar to previous years, tillage treatments had statistically non-significant effect on grain protein content. However, compared to spring wheat in 2012, grain protein levels were slightly higher in the present study under all tillage treatments. This might be possibly due to complex interaction between seedbed conditions and modification of local environment (shortage of precipitation), and lower grain yield. These observations supports Randall & Moss (1990); Borghi *et al.* (1997); Blumenthal *et al.* (1991) who reported that grain protein levels are influenced by the interaction of number of factors including crop varieties, seedbed conditions, local climate, and grain yield. In general, water stress is often associated with increased grain protein (Terman *et al.* 1996), while an excess of soil moisture reportedly cause decrease in grain protein (Robinson *et al.* 1979).

Generally, in all core experiments (2010/11, 2012 and the present study), none of the organic wheat crops grown under any cultivation treatments achieved grain protein content necessary for higher premium price (bread-making). This is not so unusual, as many previous studies have reported lower grain protein levels in organic systems (Starling & Richards 1990; Thompson *et al.* 1993a). Based on the study, it can be regarded that, although grain protein content depends on crop genotype, the potential to which it can be expressed mainly depends on prevailing environmental conditions, as compared with agricultural management practices, supporting Robinson *et al.* (1979) and Fowler *et al.* (1990)

Effect of tillage treatments on soil mineral nitrogen (SMN)

Similar to 2012 of spring wheat, more tillage intensity with CT and LRNiT had significantly higher SMN than HRNiT. This observation reconfirms Knight *et al.* (2008); Blevins and Frye (1993) and Silgram & Shepherd (1999) that the physical disruption by increased cultivations often enhances net N mineralisation through increasing aerobicity and exposure of organic matter to greater microbial decay. Similarly, House *et al.* (1984) and Varco *et al.* (1993) described that when the soils are subjected to more cultivation, and crop residues are mixed into the soil, the release of residue N tends to be faster than that of surface-placed residue associated with lower soil movements.

As with 2012 of spring wheat, the increase in SMN levels under CT and LRNiT (after cultivation) was caused by an increase in $N0_3$-N (data not shown) reconfirms higher nitrification rates by increased tillage intensity. Throughout the assessments, despite statistically non-significant wheat N concentration among tillage treatments, wheat biomass and grain yield was used as a possible indicator of nutrient uptake. Accordingly, wheat under CT followed by LRNiT had significantly higher nutrient uptake, compared with HRNiT. The utilisation of net SMN by wheat, in general, varied due to greater competition from weeds under all tillage treatments. Among tillage treatments, in particular, under LRNiT and HRNiT weeds N uptake was higher at each assessment, compared with wheat N uptake. Despite, relatively high weed density there was no evidence to suggest weeds were competing with primary crop for nitrogen due to non-significant N % under all tillage treatments. The difference in estimated SMN was notable until May. After May, there was no statistically significant difference between tillage treatments. The dry weather after May might have possibly affected the mineralisation rates. Jenkinson *et al.* (1987) and Rasmussen *et al.* (1998) reported that unlike saturated soils where lack of oxygen limits N mineralisation, for dry soils, mineralisation tends to be low because soil micro-organism activity is limited by water availability. Thus after May, the crops may have took most of the N what was available and potentially depleted soil nitrogen down to a relatively uniform level.

The SMN results from both the cropping years (2012 and 2013) showed a similar trend however, under different climatic scenario. Based on these results, it can be regarded that the differences in plant population levels, crop growth rate, rapid changes in distribution of N within plants, and consequent changes in N concentration in plant parts, and greater competition from weeds indicate the complexity of relating wheat N uptake through N analysis of plant tissues and the net SMN.

Effect of tillage treatments on soil moisture percentage

The mean soil moisture percentage indicates that non-inversion tillage systems (in particular, HRNiT) had significantly higher soil moisture levels than CT. This observation might possibly provide explanation for 2010/11 of winter wheat, that non-inversion tillage with reduced soil movements and continuous presence of soil cover has the potential to conserve (or perhaps increase) soil moisture levels than CT under dry weather. The condition of soil moisture being saved (or perhaps improved) with non-inversion tillage may be crucial for crop production in fluctuating weather patterns or in months with shortage of precipitation. According to Triplett & Dick (2008), various factors are involved in increased moisture supplies with conservation tillage; these include less soil movements, reduced evaporation from the soil surface and better utilisation of small rainfall events. Although these effects may be additive, the relative importance of each may vary with different soil types, site, crop growing season and rainfall patterns (Edwards *et al.* 1988). Unlike 2010/11 of winter wheat or previous studies (Crowling & Doring 2012; Martinez *et al.* 2008) where improved moisture content under non-inversion tillage systems was most likely explanation for increased or equivalent crop productivity to that of conventional tillage, however, in the present study, improved soil moisture levels did not necessarily favour primary crop growth by translating to higher grain yields; possibly due to greater weed prevalence.

Effect of tillage treatments on soil chemical and biological properties

In contrast to 2012 of spring wheat, where increased moist conditions may have possibly heightened soil pH (statistically significant) differences under non-inversion tillage systems, compared with CT, in the present study, soil pH was found to be statistically non-significant among tillage treatments. These contrasting results (2012 and 2013) suggest that change in the soil pH might possibly be due to larger temporal spread and environmental conditions as compared to the cultivation treatments, supporting Spiegel *et al.* (2007).

As with 2012, C_{org} and N_t were significantly higher with non-inversion tillage systems, compared with CT. In comparison to 2012 spring wheat, the present study indicated marginal increase in C_{org} and N_t with non-inversion tillage while, marginal decrease in C_{org} and N_t with conventional tillage. These observations reflect previous studies (Lopez-Garrido *et al.* 2011; Blevins & Frye 1993) that greater amounts of soil organic carbon and nitrogen in the upper soil layer with conservation tillage as a consequence of less soil movements without inversion and continuous retention of surface residues. As seen in 2012, reduction in soil tillage with continuous presence of surface soil cover with non-inversion tillage systems significantly increased earthworm numbers compared to ploughing. This observation supports Edwards & Bohlen (1996); Francis & Knight (1993) and Karlen *et al.* (1994b). However, compared to 2012 spring wheat, average earthworm density under all tillage treatments was significantly lower possibly due to dry weather situation.

4.5. Summary

Soil physical environment, delayed sowing, tillage-induced seedbed variations and greater weed competition can be cited for lower field and yield performance of wheat under non-inversion tillage systems, compared with conventional tillage, supporting previous studies of similar findings (Camara *et al.* 2003; Hammel 1989; Lopez-Bellido *et al.* 1996). Failure to control weeds from previous cropping years had substantially increased weed pressure under all tillage treatments, in particular HRNiT. The shortage of precipitation and existence of greater weed coverage affected the recovery of residual legumes and also caused failure of annual addition of legumes. Similar to previous year, increase in soil organic carbon, nitrogen, and earthworm numbers under non-inversion tillage in comparison with conventional tillage seems reassuring.

Chapter - 5

INVESTIGATIONS OF SUITABLE LEGUME SPECIES FOR UNDERSOWING IN ORGANIC SPRING WHEAT

5.1 Introduction

Mixed and intercropping of legumes are common practices in developing nations where there has been little investment in, or access to, mineral fertilisers and crop protection chemicals (Fukai 1993). In contrast, in developed countries intercropping of legumes is not more wide spread (Tilman *et al.* 2002). Industrial agricultural practices, which mainly focused on sole crops that are easier to manage, and well supplied with modern technologies of production mainly aim to maximise crop yield (Anil *et al.* 1998). Recent concerns over the negative soil and environmental impact have led to the alternate crop production strategies - including intercrops, bi-cropping and crop potential usage for suppressing and tolerating weeds (Canfield *et al.* 2010; Crews & Peoples 2004).

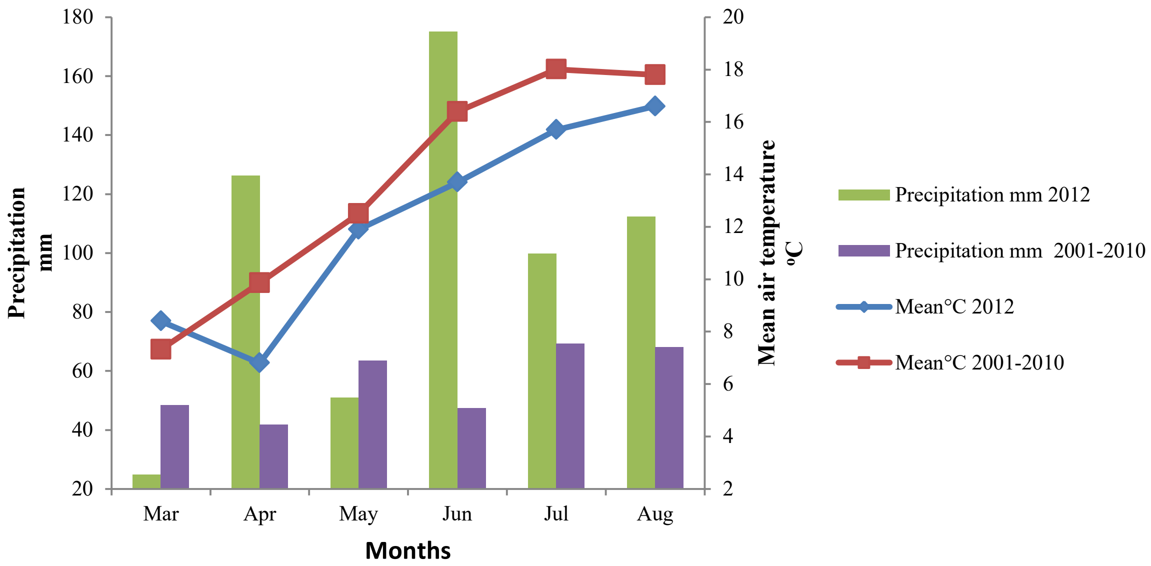
Intercropping in the UK usually takes the form of undersowing (Hartl 1989). Forage legume species are sown with cereal crops in the spring allowing the development of a subsequent ley after the harvest of the main crop (Hartl 1989). The understory crops are used not for economic yield, but for other benefits such as weed suppression (Liebman 1986) and nitrogen inputs for the subsequent crop (Thiessen Martens *et al.* 2005). Intercropping also provides other agronomic benefits including: increased biological activity by adding organic matter to the soil that can also improve soil physical structure (Duda *et al.* 2003); reduce pests and diseases (Liebman & Dyck 1993); enhanced cropping diversity that create habitats for beneficial insects and also capture and recycle soluble nutrients (Hartwig & Ammon 2002). However, competition between the undersown crop and the main crop for potential resources such as light, water and plant nutrients can greatly reduce main crop growth (Clements & Williams 1967). Papadakis (1941) and Ofori & Stern (1987) also reported that despite, land equivalent ratio is often higher in comparison to monoculture, cereal-legume intercrops generally yield lower than they do in monoculture. Nevertheless, mixing species in cropping systems may possibly lead to a range of benefits that are expressed on various space and time scales, from a short-term increase in crop yield and grain protein content to long term agro-ecosystem sustainability (Malezieux *et al.* 2009). A field study was therefore, conducted to compare the influence of different undersown legume species and to possibly identify suitable legumes for undersowing in organic spring wheat.

5.2 Materials and Methods

5.2.1 Site details

The study was conducted from March 2012 to August 2012 in an adjacent field (of main study) previously cropped with organic winter wheat cv. Claire (core experiment -I) at the Royal Agricultural University's Harnhill Manor Farm (NGR SP 075 006). The soil texture was clay and pH of 7.7. Soil phosphorus and potassium indices were 13.2mgl^{-1}or Index 1 and 200mgl^{-1} or Index 2. Index value rated according to DEFRA (2010). The average air temperature and seasonal precipitation during 2012 spring wheat cropping period was 12.2^{o}C and 589.1mm. The 2012 of spring wheat experienced lower spring and summer time average air temperatures, and precipitations were much higher throughout the growing season, compared to long-time seasonal average (Figure 5.1).

Figure 5.1 Mean air temperature and amount of precipitation during 2012 crop season. Royal Agricultural University Meteorological station, (NGR SP 42 004 011)



5.2.2 Experimental design and treatment structure

The experimental design (Figure 5.2) was a one factor randomized block design with four replications. On 10 March 2012, the field was ploughed using a mouldboard plough followed by secondary cultivation operations with a power harrow combination seed drill. Spring wheat cv. Paragon at 420 seeds m^{-2} was drilled on 14 March 2012. On 11 April 2012 a block of 24m × 3m was set up, and split into eight, each plot size measuring 3m × 3m and undersown (broadcasting by hand) with seven different legume species and one non-undersown control (N_{us}) treatments. The legume species undersown were white clover (WC) (*Trifolium repens* L. Nemuniai org; 1g m^{-2}), black medic (BM) (*Medicago lupulina* L. Virgo; 1g m^{-2}), bird's foot trefoil (BT) (*Lotus carniculatus* L. Leo; 1g m^{-2}), vetch (V) (*Vicia sativa* L. Early English org; 8.5g m^{-2}), red clover (RC) (*Trifolium pratense* L. quinequel org; 1.5g m^{-2}), crimson clover (CC) (*Trifolium incarnatum* L. Rosa org; 1.5g m^{-2}) and persian clover (PC) (*Trifolium respinatum* L. Marco polo org; 1g m^{-2}); the plots were hand harvested on 22 August 2012. Optimum seed rate recommended by Cotswold Seeds Ltd were considered.

Figure 5.2 Trial design for undersowing treatments

BM	BT	C	CC	RC	WC	V	PC
BT	V	RC	WC	PC	BM	CC	C
V	RC	PC	C	CC	WC	BM	BT
WC	BM	BT	V	PC	CC	RC	C

3m 3m

BM – Black medic, WC – White clover, BT- Bird's foot trefoil, RC- Red clover, PC – Persian clover, CC- Crimson clover, C- Control (no undersowing), V- Vetch

5.2.3 Assessments

Above ground assessments (Table 5.1) conducted using the same protocol and formula as in Chapter – 2, core experiment – I, §2.2.4.

Table 5.1 Above ground assessments for spring wheat

Assessments	Sample size	Date/Approximate growth stages
Wheat plant heights	At two random points from each plot	05 August 2012
Number of wheat ears	0.1m^2 quadrat randomly with two replications per plot	05 August 2012
Final biological harvest	0.1m^2 quadrat randomly with two replications per plot	22 August 2012

5.2.4 Data analysis

Statistical analysis and reporting results, as stated in Chapter – 2, core experiment – I, §2.2.5. One way (in Randomized Blocks) analysis of variance (ANOVA) was used to establish the performance of undersowing treatments.

5.3 Results

Plant heights and ear numbers

Comparing non-undersown with different legume species undersown (Table 5.2) significantly shorter wheat plants and lower ear numbers were observed when PC, CC, RC and V were undersown.

Table 5.2 Wheat crop height and ear numbers among undersowing treatments

	Plant height (cm)	Ear (numbers m^{-2})
Non-undersown	81.52a	372a
Wheat + WC	81.16a	360a
Wheat + BM	80.66ab	335ab
Wheat + BT	80.44ab	328ab
Wheat + V	79.25b	307bc
Wheat + RC	77.17c	290bc
Wheat + CC	76.30cd	286bc
Wheat + PC	75.14d	275c
SED (53 df)	0.86*	24.81*

Values followed by the same letter do not differ significantly (p <0.05)*

Final biological harvest

In comparison to non-undersown (Table 5.3), ears DM and straw DM were significantly lower when PC, CC, RC, V, and BT were undersown. Grain yield also showed a similar trend to that of ear DM and straw DM. There was no statistically significant difference on TGW and harvest index between undersowing treatments. Compared with non-undersown (Table 5.4), total grain N uptake was significantly lower with RC, CC, and PC. Total wheat N uptake showed a similar trend to that of grain yield and straw DM. There was statistically non-significant undersowing treatment effects on grain protein content and nitrogen harvest index.

Table 5.3 Wheat yield performance among undersowing treatments

	Ear DM (t ha^{-1})	Straw DM (t ha^{-1})	TGW (g)	Grain yield (t ha^{-1})	Harvest Index (%)
Non-undersown	5.00d	4.37c	34.73a	3.79a	39.92a
Wheat + WC	4.50bcd	4.39c	34.24a	3.61ab	40.51a
Wheat + BM	4.61cd	3.91bc	34.36a	3.51ab	40.98a
Wheat + BT	4.00abc	3.35ab	33.70a	2.92bc	40.50a
Wheat + V	3.98abc	3.31ab	33.39a	2.84bc	39.73a
Wheat + RC	3.60ab	3.15ab	33.64a	2.62c	36.74a
Wheat + CC	3.48a	3.12a	32.83a	2.52c	37.73a
Wheat + PC	3.30a	2.95a	32.16a	2.27c	35.80a
SED (53 df)	0.482*	0.391*	1.319^{ns}	0.412*	3.164^{ns}

Values followed by the same letter do not differ significantly ($p < 0.05$, ^{ns} $p > 0.05$)*

Table 5.4 Wheat nitrogen yields among undersowing treatments

	Total grain N uptake (kg ha^{-1})	Total wheat N uptake (kg ha^{-1})	Nitrogen harvest index (%)	Grain protein content (%)
Non-undersown	68.1b	92.4c	76.36a	10.27a
Wheat + WC	68.6b	93.1c	77.11a	10.85a
Wheat + BM	65.9b	87.8bc	76.98a	10.66a
Wheat + BT	54.6ab	72.7ab	77.48a	10.59a
Wheat + V	53.6ab	71.5ab	76.72a	10.80a
Wheat + RC	48.9a	66.6a	77.60a	10.50a
Wheat + CC	46.0a	64.3a	75.87a	10.49a
Wheat + PC	41.7a	57.4a	77.22a	10.44a
SED (53 df)	7.80*	8.31*	1.036^{ns}	0.289^{ns}

Values followed by the same letter do not differ significantly ($p < 0.05$, ^{ns} $p > 0.05$)*

Among undersown legume species (Table 5.5), the growth, establishment and dry matter of PC was significantly higher, compared with BT, BM, and WC. Non-undersown plots were not completely free of legumes. Natural regeneration of the previous ley, spatial nature of the experimental design, weather conditions, and method of seeding might have caused contamination. The legumes (under non-undersown) were separated from other broadleaf weeds, even though they were legume weeds rather than undersown legumes. Nevertheless, legumes DM under non-undersown treated plots were significantly lower than undersown legume plots. Relative to weeds DM, there was statistically non-significant difference among undersowing treatments although, the observed trend showed increased weeds DM under all undersown treatment plots, compared with non-undersown. Among non-wheat DM, undersowing with PC, CC, RC, V, and BT showed significantly higher non-wheat DM yields than non-undersown. The total N uptake by legumes and weeds showed a similar trend to that of their respective dry matter yields.

Table 5.5 Legume and weeds biomass and their nitrogen yields among undersowing treatments

	Legume DM ($t\ ha^{-1}$) (a)	Weeds DM ($t\ ha^{-1}$) (b)	Total legumes N uptake ($kg\ ha^{-1}$) (c)	Total weeds N uptake ($kg\ ha^{-1}$) (d)	Non-wheat DM ($t\ ha^{-1}$) (a + b)	Total non-wheat N up take ($kg\ ha^{-1}$) (c + d)
Non-undersown	0.130a	0.172a	3.62a	3.15a	0.307a	6.76a
Wheat + WC	0.258b	0.195a	6.82ab	3.14a	0.452ab	9.96ab
Wheat + BM	0.264b	0.226a	7.02abc	3.63a	0.489abc	10.65ab
Wheat + BT	0.272b	0.245a	7.75bcd	4.42a	0.517bc	12.18abc
Wheat + V	0.293bc	0.278a	8.34bcd	5.28a	0.571bc	13.62bcd
Wheat + RC	0.298bc	0.265a	8.74bcd	4.80a	0.563bc	13.54bcd
Wheat + CC	0.358bc	0.309a	10.52cd	5.98a	0.667c	16.50cd
Wheat + PC	0.393c	0.282a	11.25d	6.87a	0.675c	18.11d
SED (53 df)	0.0580*	0.0836^{ns}	1.82*	1.88^{ns}	0.104*	2.80*

Values followed by the same letter do not differ significantly ($p < 0.05$, ^{ns} $p > 0.05$)*

5.4 Discussion

The undersown legume species were initially chosen based on diversity in growth rates, crop heights, upright or prostrate growth or seed weight, as described by Ross *et al.* (2001). Increased precipitation during their cropping period favoured the growth, establishment, and biomass production of undersown legume species. Similar observation was also reported by Kankanen *et al.* (2001) that higher precipitation in spring and early summer resulted in positive undersown cover crop dry matter production.

Wheat grain yield appear to be positively related to plant height, ear number and wheat ear and straw DM, and negatively related to legume DM or non-wheat DM yields (legumes and weeds DM). The ability of undersown legume species to grow tall, upright and yield higher dry matter showed a significantly negative effect on yield components and grain yield, compared with non-undersown. This observation supports Clements & Williams (1967) who reported that, as undersown legume species grow, competition between undersown crop and the cash crop for potential resources can greatly reduce main crop growth and yield compared to monoculture.

Weeds DM, although, were statistically non-significant, the legume species undersown did not restrict weeds, rather undersown treatment plots showed a tendency towards higher weeds DM. Teasdale *et al.* (1991); Akemo *et al.* (2000) also observed that a type of undersown cover crop may possibly reduce or increase or have no effect on weeds, which reveals the complexity of undersowing practices on weed infestation. Other researchers have also reported that undersowing cover crops reduced weeds, but not enough to eliminate the need for chemical control (Yenish *et al.* 1996; Curran *et al.* 1994; Johnson *et al.* 1993). The increase in legume species DM indirectly caused an increase in non-wheat DM, with PC, CC, RC, V, and BT had significantly higher non-wheat DM, compared with non-undersown control. This condition of direct and indirect effects of undersown legume species contributed to greater competition in the growing environment, and may have negatively impacted on factors which influenced yield and leading to lower grain yield. This observation supports Liebman & Dyck (1993) who reported that the success of cereal-legume bi-cropping not only depends on the undersown legume species complementing with the main crop, but also on the infestation of weed population density. Similar results of variable crop yields and greater legume and weeds competition under cereal-legume intercropping than mono-cropping was also reported by Pridham & Entz (2008). However, this study finding contradicted Reynolds *et al.* (1994); Jensen (1996) and Hauggaard-Nielsen *et al.* (2008) who all reported that introducing a legume intercrop to cereal systems in organic or low input environment increased grain yields, grain protein content and also reduced weed biomass. Nevertheless, the present study showed that the growth potential and pattern of the undersown cover crop are also important, and the success among intercrops depends on the cash crop, time of sowing, weed pressure, and environmental conditions, as reported by Blackshaw *et al.* (2010) and Lithourgidis *et al.* (2011).

Spring wheat undersown with legume species showed a tendency towards higher grain protein content, compared with non-undersown, although, the results were statistically non-significant. Generally, nitrogen is usually limited under organic farming conditions (Thompson *et al.* 1993a). Against this condition, this study like many previous studies (Bond & Grundy 2001; Walker *et al*. 1956; Clark *et al.* 1999) the non-significant N % from crop species indicates that there might be greater inter-specific competition other than just for nitrogen during growth. This competition might have influenced the primary crop survival, growth, and dry matter production among undersowing treatments. Undersowing into low yielding and shorter season organic spring wheat crop may perhaps magnify the negative effects of intercropping through greater competition in a growing environment from the legumes and weeds, supporting William & Hayes (1991); Koefoed *et al.* (1997) and Clements *et al.* (1996b).

5.5. Summary

Under the soil and weather conditions which prevailed during this study, prostrate growing WC and BM appear to be more suitable than the other legume species. Undersowing upright and fast growing legume species while the wheat is still establishing may compete strongly with the main crop. Furthermore, undersowing into the emerged stand may also compete less with weeds (Ohlander *et al.* 1996). The type of legume species undersown can exhibit direct and indirect effects, therefore, causing lower yields compared to wheat alone. In addition, this study also confirms that the selection of WC and BM for undersowing than other legume species, proved to be suitable for establishing the core experiments.

Chapter- 6

ENERGY AND ECONOMIC CONSIDERATION OF DIFFERENT TILLAGE AND LEGUME UNDERSOWING IN ORGANIC WHEAT PRODUCTION

6.1 Introduction

Developed nations such as the UK are trying to minimise traffic and field operations in their farms (Morris *et al.* 2010). The use of combined cultivation machines, therefore, has become increasingly popular. Combined cultivation machines are the most effective ways of reducing energy consumption and cost of field operations (Hernanz *et al.* 1995). According to Pimentel *et al.* (1994) energy, economics and the environment are mutually dependent. The amount of energy used depends on the mechanization level, quantity of active agricultural work and cultivable land area (Lawrence *et al.* 1994). Energy demand in agriculture can be divided into direct and indirect support energies (Tabatabaeefar *et al.* 2009). Direct support energy is required for land preparation, harvest, post-harvest processing, and the transportation of agricultural inputs and outputs (Tabatabaeefar *et al.* 2009). Indirect support energy is used in the form of fertilizers and pesticides (Bailey 2003). However, such indirect energy options are greatly limited under organic management (Adl *et al.* 2011; Pimentel *et al.* 2005).

In the cultivation of arable crops, conventional tillage is one of the greatest energy and labour consumers (Epplin *et al.* 2005). In contrast, reducing tillage reduces fuel consumption and decreases time, and energy required for seedbed preparation (Clements *et al.* 1995). Carter *et al.* (2003b) reported that work rates are much improved under non-inversion tillage systems and thereby, offering greater flexibility and timeliness for weather dependent operations. In general, energy-use of resources is one of the key indicators of sustainable agricultural practices as it helps financial savings, fossil fuel preservation and also reduces air pollution (Streimikiene *et al.* 2007). The aim of this study, therefore, was to assess energy budgets (by transforming the data using energy equivalent values) and also economics (based on contractors costs) of using multi-tooled cultivation techniques involving conventional tillage (CT), low residue non-inversion tillage (LRNiT) and high residue non-inversion tillage (HRNiT) and also undersowing black medic (BM) or white clover (WC) against non-undersown (N_{us}) on organic winter and spring wheat production.

6.2 Materials and Methods

6.2.1 Treatment structure, assessments, and data analysis

Experimental design, treatments structure and the details of husbandry practices have been previously reported in Chapter – 2, core experiment – I, §2.2.3, Chapter – 3, core experiment – II, §3.2.1 and Chapter – 4, core experiment – III, §4.2.1.

Energy assessments

To specify the input (direct and indirect) and output energy for wheat production, the amount of each input such as human labour, machinery, seed and diesel fuel and output in terms of wheat yield were taken into consideration. To calculate the amount of energy values for inputs and outputs (as physical data), the energy equivalent values (Table 6.1) were applied. The specifications of the machinery used in the core experiments were listed in Table 6.2. The working width, depth, and speed of work for each operation (CT, LRNiT, and HRNiT) were recorded with overall efficiency of 80% for primary and 70% for secondary operations. The energy use efficiency, energy specific, energy productivity and net energy gain was calculated using the following formula (Mohammadi *et al.* 2008).

$$\text{Energy use efficiency} = \frac{\text{Output energy (MJ ha}^{-1})}{\text{Input energy (MJ ha}^{-1})}$$

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

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

$$\text{Net energy gain} = \text{Output energy (MJ ha}^{-1}) - \text{Input energy (MJ ha}^{-1})$$

The input energy was divided into direct and indirect support energies (Ozkan *et al.* 2004). Direct energy includes human labour and diesel fuel while, indirect energy includes seed and machinery energy. Renewable energy consists of seed and human labour and non-renewable energy includes machinery and diesel fuel (Tabatabaeefar *et al.* 2009).

Table 6.1 Energy equivalent indicators of inputs and outputs

Factor	Unit	Energy equivalent (MJ/unit)	Reference
<u>Input</u>			
Human labour	h ha^{-1}	1.87	Smil (1983)
Machinery	h ha^{-1}	62.7	Erdal *et al.* (2007)
Diesel fuel	L ha^{-1}	41.0	Reinhardt (1993)
Seed (wheat)	kg	25	Ozkan *et al.* (2004)
Legume seed	kg	14.7	Kitani (1999)
<u>Output</u>			
Grain yield	kg	14.7	Pimentel (1980)

Table 6.2 The Specifications of the 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) (5080kg)	5 furrow Kverneland plough + press	1.8	20	7	1	1	23
	Power harrow seed drill	3	8	8	1.7	0.97	15
LRNIT TM 155 (154 HP, 4wd) (5642kg)	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
HRNIT TM 155 (154 HP, 4wd) (5642kg)	1 pass of ST bar attached Simba X-press	3	25 & 12	10	2.4	0.7	14
	Eco-dyn seed drill	3	26	9	1.9	0.88	10

Economic assessments

Price consideration was applied based on the price quoted from the 2011/12 Organic Farm Management Handbook (Lampkin *et al.* 2011). The raw data of grain yield and protein content from each core experiments were used to calculate grain price and other applied economics. All the contractor costs have been listed under Royal Agricultural University's Farm records. Total variable costs include contractor cost (that included fuel, labour and transportation of seeds) for land preparation and drilling, and legume (WC and BM) seed cost. Total production costs was the sum of total variable costs, wheat seed cost (winter or spring) and combine harvesting cost (including carting and filling stage). For the purpose of calculating total production and variable costs the following parameters as listed in Table 6.3 were applied.

Table 6.3 Seed costs, contractor costs and grain price considered for all core experiments

	Parameter	Costs	Source
Winter wheat	193kg ha^{-1} @ £600 t^{-1}	£116 ha^{-1}	Lampkin *et al.* (2011)
Spring wheat	197kg ha^{-1} @ £600 t^{-1}	£118 ha^{-1}	Lampkin *et al.* (2011)
White clover	7 kg ha^{-1}	£55.30	Cotswold Seeds Ltd.
Black medic	8 kg ha^{-1}	£73.08	Cotswold Seeds Ltd.
CT	Kverneland reversible plough + Power harrow combination seed drill	£50 ha^{-1} & £45 ha^{-1}	Royal Agricultural University's Farm records
LRNiT	2 passes of ST bar attached Simba X-press + Vaderstadt seed drill	£62 ha^{-1} & £31 ha^{-1}	Royal Agricultural University's Farm records
HRNiT	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
Combine harvesting		£80 ha^{-1}	Royal Agricultural University's Farm records
Grain price (winter or spring)	grain protein < 11%	£270 t^{-1}	Lampkin *et al.* (2011)
Grain price (winter or spring)	grain protein > 11%, premium £25 t^{-1}	£295 t^{-1}	Lampkin *et al.* (2011)

Economic analysis of wheat production including total production value, gross return, net return, and benefit-cost ratio was calculated using the following formula (Zangeneh *et al.* 2010).

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

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

$$\text{Benefit-cost ratio} = \frac{\text{Total production value (£ ha}^{-1}\text{)}}{\text{Total production costs (£ ha}^{-1}\text{)}}$$

General calculations were performed using Microsoft Excel – 2010. Energy budgets and applied economics was analysed using the split plot analysis of variance (ANOVA) model in in Genstat (15th Edition VSN International Ltd, Hemel Hempstead, UK). Reporting results, as stated in Chapter – 2, core experiment – I, §2.2.5.

6.3 Results and Discussion

Energy analysis

It is recognized that crop production, grain yields, and food supplies are directly linked to energy (Stout 1990). The energy use in agriculture has been increasing in response to growing population, limited availability of arable lands and increased mechanization (Ozkan *et al.* 2011). The input and output energy are the two key factors for identifying the energy and ecological efficiency of a crop production. The need, therefore for an assessment of energy inputs-use efficiency among various husbandry practices of organic farming would be valuable. Although, previous studies have assumed various energy equivalent values (Ozkan *et al.* 2011; Erdal *et al.* 2007), due to the limited availability and inconsistent supply of data, energy equivalents listed in Table 6.1 was used and applied across all the husbandry treatments. Hence, by applying these energy equivalents to transform input and output data will help recognize energy-use efficiency among the practiced husbandry treatments. The total inputs including direct, indirect, renewable, and non-renewable inputs used for organic winter and spring wheat production and their energy equivalents were illustrated in the Table 6.4, 6.5 and 6.6.

The results (from Table 6.5 and 6.6) indicate that direct input energy was less compared to indirect input energy under all cultivation treatments. This implies that the organic wheat (winter or spring) production is mainly dependent on mechanization and seed. Among cultivation treatments, regardless of wheat type, direct energy, indirect energy and hence the total inputs energy was higher with CT followed by LRNiT, compared with HRNiT. This is due to the increased requirement for diesel fuel, human labour, and machinery energy to carry out seedbed preparation. The renewable energy was relatively similar under all tillage treatments. However, the highest share was from seed. This is not so unusual, as higher seeding rate (or seed energy) is often used under organic farming, compared to conventional (Lampkin *et al.* 2011; Hiltbrunner *et al.* 2007b). The non-renewable energy was lower with HRNiT followed by LRNiT, compared with CT. This is because of lower machinery and diesel fuel energy required to carry out seedbed operations. In general, irrespective of tillage treatments and wheat types, the decrease in non-renewable energy, compared to renewable energy, might be due to the multi-tooled cultivation approach, that substantially saved field operations including diesel fuel, labour and machinery energy.

Table 6.4 Amounts of inputs and their equivalent energy from calculated indicators of energy (winter wheat 2010/11and spring wheat 2012 and 2013)

	Human labour (h ha^{-1}) (a)	Machinery (h ha^{-1}) (b)	Diesel fuel (L ha^{-1}) (c)	Wheat seed (kg ha^{-1}) (d)	Spring wheat (kg ha^{-1}) (e)	Legume seed (kg ha^{-1}) (f)	Labour for broadcast (h ha^{-1}) (g)
CT (N_{us})	7.424	248.92	2501	4825	4925	-	-
CT (WC)	7.424	248.92	2501	4825	4925	102.9	2.81
CT (BM)	7.424	248.92	2501	4825	4925	117.6	2.81
LRNiT (N_{us})	7.480	250.80	2337	4825	4925	-	-
LRNiT (WC)	7.480	250.80	2337	4825	4925	102.9	2.81
LRNiT (BM)	7.480	250.80	2337	4825	4925	117.6	2.81
HRNiT (N_{us})	6.695	224.47	1927	4825	4925	-	-
HRNiT (WC)	6.695	224.47	1927	4825	4925	102.9	2.81
HRNiT (BM)	6.695	224.47	1927	4825	4925	117.6	2.81

Table 6.5 Direct and indirect input energy for winter wheat 2010/11

	Total input energy equivalents (MJ ha^{-1}) (a+ b+c+d+f+g)	Direct energy (MJ ha^{-1}) (a + c + g)	Indirect energy (MJ ha^{-1}) (b+d+f)	Renewable energy (MJ ha^{-1}) (a+d+f+g)	Non-renewable energy (MJ ha^{-1}) (b+c)
CT (N_{us})	7582.34	2508.42	5073.92	4832.42	2749.92
CT (WC)	7688.05	2511.23	5176.82	4938.13	2749.92
CT (BM)	7702.75	2511.23	5191.52	4952.83	2749.92
Average	***7657.72***	***2510.29***	***5147.42***	***4907.80***	***2749.92***
LRNiT (N_{us})	7420.28	2344.48	5075.80	4832.48	2587.80
LRNiT (WC)	7525.99	2347.29	5178.70	4938.19	2587.80
LRNiT (BM)	7540.69	2347.29	5193.40	4952.89	2587.80
Average	***7495.65***	***2346.35***	***5149.30***	***4907.85***	***2587.80***
HRNiT (N_{us})	6983.17	1933.70	5049.47	4831.70	2151.47
HRNiT (WC)	7088.88	1936.51	5152.37	4937.41	2151.47
HRNiT (BM)	7103.58	1936.51	5167.07	4952.11	2151.47
Average	***7058.54***	***1935.57***	***5122.97***	***4907.07***	***2151.47***

Table 6.6 Direct and indirect input energy for spring wheat 2012 and 2013

	Total input energy equivalents (MJ ha^{-1}) (a+b+c+e+f+g)	Direct energy (MJ ha^{-1}) (a + c + g)	Indirect energy (MJ ha^{-1}) (b+e+f)	Renewable energy (MJ ha^{-1}) (a+e+f+g)	Non-renewable energy (MJ ha^{-1}) (b+c)
CT (N_{us})	7682.34	2508.42	5173.92	4932.42	2749.92
CT (WC)	7788.05	2511.23	5276.82	5038.13	2749.92
CT (BM)	7802.75	2511.23	5291.52	5052.83	2749.92
Average	***7757.72***	***2510.29***	***5247.42***	***5007.80***	***2749.92***
LRNiT (N_{us})	7520.28	2344.48	5175.80	4932.48	2587.80
LRNiT (WC)	7625.99	2347.29	5278.70	5038.19	2587.80
LRNiT (BM)	7640.69	2347.29	5293.40	5052.89	2587.80
Average	***7595.65***	***2346.35***	***5249.30***	***5007.85***	***2587.80***
HRNiT (N_{us})	7083.17	1933.70	5149.47	4931.70	2151.47
HRNiT (WC)	7188.88	1936.51	5252.37	5037.41	2151.47
HRNiT (BM)	7203.58	1936.51	5267.07	5052.11	2151.47
Average	***7158.54***	***1935.57***	***5222.97***	***5007.07***	***2151.47***

Statistical analysis of energy indices for winter wheat in 2010/11 (Table 6.7) revealed that among tillage treatments, CT had significantly higher output energy (13.43 MJ ha^{-1}) per unit of input energy, compared to HRNiT (11.51 MJ ha^{-1}). Similarly, the energy productivity was also significantly higher with CT than HRNiT. Specifying that 0.914 kg MJ^{-1} of output obtained per unit energy with CT, compared to 0.783 kg MJ^{-1} with

HRNiT. The energy intensity was significantly higher with HRNiT, compared with CT. This is because despite low input energy, the yield with HRNiT also decreased significantly. Implying that 1.339 MJ kg^{-1} of input acquired per unit yield with HRNiT, compared with 1.118 MJ kg^{-1} of CT. Net energy indicates the difference between the gross energy output produced and the total energy used for obtaining it. Accordingly, the estimated values indicate that CT and LRNiT had significantly higher net energy gain, despite higher energy inputs, compared to HRNiT. Generally, energy efficiency and energy productivity can be increased either by decreasing total energy input or by increasing total energy output, and by applying both specified actions at the same time (Zentner *et al.* 2004). Despite the fact that direct, indirect and hence total input energy was lower with HRNiT; the output energy in terms of grain yield was also substantially lower than other treatments. Maximum reduction in tillage intensity and retention of >50% surface soil cover with HRNiT, produced a much coarser seedbed than LRNiT and CT which adversely impacted on plant establishment, crop growth and therefore crop yield (Vijaya Bhaskar *et al.* 2013a). Similar results were also reported by Borin *et al.* (1997) that decreasing tillage intensity reduces output energy, therefore, overall energy efficiency.

Table 6.7 Analysis of energy indices for organic winter wheat 2010/11

	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	6995a	102827	13.43a	0.914a	1.118a	95170a
LRNiT	6583a	96772	12.91ab	0.878ab	1.194ab	89276a
HRNIT	5529b	81277	11.51b	0.783b	1.339b	74218b
SED (10 df)	316.8*	-	0.635*	0.0432*	0.0740*	4656.5*

Values followed by the same letter do not differ significantly (p <0.05)*

Among cultivation treatments, for spring wheat in 2012 and 2013, the statistical analysis of energy indices (Table 6.8 and 6.9) showed that CT had significantly higher output energy (6.67 and 5.86 MJ ha^{-1}) per unit of input energy followed by LRNiT (5.72 and 4.30 MJ ha^{-1}), compared with HRNiT (4.34 and 2.74 MJ ha^{-1}). Similarly, the energy productivity was also significantly higher with CT followed by LRNiT, compared with HRNiT. This indicated that 0.453 kg MJ^{-1} and 0.399 kg MJ^{-1} of output obtained per unit energy with CT, compared to 0.389 kg MJ^{-1} and 0.292 kg MJ^{-1} with LRNiT or 0.295 kg

MJ^{-1} and 0.186 kg MJ^{-1} with HRNiT. The specific energy required per unit yield was significantly higher with HRNiT than LRNiT or CT for spring wheat 2012. However for spring wheat in 2013 such differences were not observed statistically, despite energy intensity value being higher under HRNiT. The net energy gain for spring wheat in 2012 and 2013 were significantly higher with CT followed by LRNiT, compared with HRNiT. Overall it can be regarded that decreasing tillage intensity (or input energy), the yield (or output energy) also tends to decrease substantially. This situation has been a widely reported concern in adopting non-inversion tillage systems such as HRNiT for organic farming (Wilkins *et al.* 1989; Blackshaw *et al.* 2001a). Despite benefits in terms of saving work duration, fuel consumption and better work rate with non-inversion tillage systems (such as HRNiT), the coarser seedbed condition, poor plant establishment, and greater weeds competition (Vijaya Bhaskar *et al.* 2013b) affected the overall energy-use efficiency.

Undersowing effects on energy indices were observed only in 2012 of spring wheat (Table 6.8). Among undersowing, all the tested energy indices such as energy ratio, energy productivity, and net energy gain were significantly greater with N_{us} than BM. The greater competition from BM and weeds caused significantly lower grain yield (or output energy), compared with N_{us} (Vijaya Bhaskar *et al.* 2013b). In contrast, the positive effects of WC on weeds (Vijaya Bhaskar *et al.* 2013b) resulted in statistically non-significant difference in analysed energy indices, compared with $N_{us.}$

Table 6.8 Analysis of energy indices for organic spring wheat 2012

	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	3516a	51684	6.67a	0.453a	2.32b	43926a
LRNiT	2955b	43439	5.72b	0.389b	2.78b	35843b
HRNIT	2114c	31069	4.34c	0.295c	4.12a	23911c
SED (10 df)	152.4*	-	0.313*	0.0213*	0.400*	2240.0*
BM	2573b	37822	4.98b	0.339b	3.35a	30273b
N_{us}	3125a	45938	6.15a	0.418a	2.72a	38509a
WC	2886ab	42431	5.60ab	0.381ab	3.15a	34897ab
SED (30 df)	161.6*	-	0.318*	0.0216*	0.323^{ns}	2375.0*

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05, ^{ns}p >0.05)*

Table 6.9 Analysis of energy indices for organic spring wheat 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	3100a	45492	5.86a	0.399a	2.56a	37734a
LRNiT	2220b	32656	4.30b	0.292b	4.37a	25061b
HRNIT	1330c	19594	2.74c	0.186c	8.09a	12435c
SED (4 df)	225.6*	-	0.529*	0.0374*	2.21 ^{ns}	4064.6*

Values followed by the same letter do not differ significantly ($p < 0.05$, ^{ns} $p > 0.05$)*

Economic analysis

Irrespective of wheat types, the contractor cost for land preparation and drilling with HRNiT was lower, compared with LRNiT or CT. Among cultivation treatments, for winter wheat in 2010/11 (Table 6.10) CT and LRNiT had significantly higher gross return, compared with HRNiT. Despite lower contractor cost for land preparation and drilling (variable costs), the substantial reduction in yield impacted on total production value, which resulted in lower gross margin compared to CT or LRNiT. The benefit to cost ratio was also significantly lower with HRNiT, compared with CT. Implying that production values with non-inversion tillage systems such as HRNiT have not rewarded with lower production costs. Among undersowing, benefit to cost ratio was higher with $N_{us,}$ compared with WC or BM. The increase in production costs and failure of legumes (due to dry weather) to provide a substantial yield advantage over non-undersown (Vijaya Bhaskar *et al.* 2013b) resulted in significantly lower benefit to cost ratio.

Table 6.10 Economic analysis of organic winter wheat production 2010/11

	Yield (t ha^{-1})	Price (£ t^{-1})	Total production value (£ ha^{-1})	Variable cost (£ ha^{-1})	Total cost of production (£ ha^{-1})	Gross return (£ ha^{-1})	Benefit to cost ratio
CT	7.00a	270	1889	137.79	333.79	1751a	5.73a
LRNiT	6.58a	270	1777	133.79	329.79	1644a	5.45ab
HRNIT	5.53b	270	1493	107.79	303.79	1385b	4.96b
SED (10 df)	0.317*	-	-	-	-	85.5*	0.280*
BM	6.13a	270	1654	156.75	352.75	1498a	4.69c
N_{us}	6.40a	270	1729	83.67	279.67	1645a	6.16a
WC	6.58a	270	1775	138.97	334.97	1637a	5.29b
SED (30 df)	0.310 ^{ns}	-	-	-	-	83.6 ^{ns}	0.277*

Values followed by the same letter for cultivation or undersowing treatments do not differ significantly ($p < 0.05$, ^{ns} $p > 0.05$)*

For spring wheat in 2012 and 2013 (Table 6.11 and 6.12) the gross return was significantly higher with CT followed by LRNiT, compared with HRNiT. The reduction in variable costs with non-inversion tillage systems also substantially decreased production value, compared with CT, thereby affecting the gross return. Although the production costs were relatively similar with CT and LRNiT, the benefit to cost ratio indicates that the seedbed condition developed with greater tillage intensity and maximum dispersion of soil cover with CT delivered better production value. Among undersowing for spring wheat in 2012, WC had significantly higher premium price than BM or N_{us}. Although, the grain protein content appear statistically non-significant between undersowing treatments (see core experiment II), consistent higher grain protein content (raw data with >11.0%) with WC undersown spring wheat has the potential to fetch significantly higher price premium in the organic markets, compared with BM or N_{us}. The gross return also indicates that WC seems a reliable option than BM, compared with $N_{us.}$ Nevertheless, all the benefits of undersowing have been occurred with a decrease in benefit to cost ratio, compared with N_{us}. This might be either due to higher production costs compared to the production value or lower production value compared to the invested costs. However, for spring wheat in 2013, undersowing treatments had no significant effects on gross return. This might be due to comparable yield or production value (statistically non-significant, see core experiment III) than the non-undersown. But, benefit-cost ratio indicates that BM had significantly lower production value per unit of production costs, compared to WC or $N_{us.}$

Table 6.11 Economic analysis of organic spring wheat production 2012

	Yield (t ha^{-1})	Price (£ t^{-1})	Total production value (£ ha^{-1})	Variable cost (£ ha^{-1})	Total cost of production (£ ha^{-1})	Gross return (£ ha^{-1})	Benefit to cost ratio
CT	3.52a	283.89a	996	137.79	335.79	858a	3.01a
LRNiT	2.96b	276.94a	820	133.79	331.79	686b	2.51b
HRNIT	2.11c	279.03a	590	107.79	305.79	482c	1.97c
SED (10 df)	0.152*	3.82 ^{ns}	-	-	-	45.8*	0.148*
BM	2.57b	278.33b	718	156.75	354.75	561b	2.01c
N_{us}	3.13a	276.25b	863	83.67	281.67	779a	3.04a
WC	2.89ab	285.28a	825	138.97	336.97	686a	2.43b
SED (30 df)	0.162*	3.011*	-	-	-	46.7*	0.144*

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05, ^{ns} p >0.05)*

Table 6.12 Economic analysis of organic spring wheat production 2013

	Yield ($t\ ha^{-1}$)	Price (£ t^{-1})	Total production value (£ ha^{-1})	Variable cost (£ ha^{-1})	Total cost of production (£ ha^{-1})	Gross return (£ ha^{-1})	Benefit to cost ratio
CT	3.10a	282.5a	874	137.79	335.79	736a	2.61a
LRNiT	2.22b	283.9a	631	133.79	331.79	497b	1.91b
HRNIT	1.33c	283.9a	376	107.79	305.79	268c	1.26c
SED (4 df)	0.226*	4.32^{ns}	-	-	-	78.5*	0.221*
BM	2.16a	278.3a	596	156.75	354.75	439a	1.66b
N_{us}	2.11a	285.3a	599	83.67	281.67	515a	2.11a
WC	2.38a	286.7a	687	138.97	336.97	548a	2.02a
SED (12 df)	0.180^{ns}	4.68^{ns}	-	-	-	55.9^{ns}	0.141*

*Values followed by the same letter for cultivation or undersowing treatments do not differ significantly (*p <0.05, ^{ns}p >0.05)*

6.4. Summary

The study aimed to reveal more economical and efficient use of energy between different husbandry treatments. Unlike conventional farming, indirect support energies are greatly restricted under organic farming situation. As a result, the performance of organic crops highly depended on environmental condition where agricultural activity is performed. Against this situation, for any given core experiment, CT had higher energy inputs and production costs. The energy outputs and production value, however, was also significantly higher with CT than other cultivation treatments. Although, non-inversion tillage systems in particular, HRNiT reduced input energy and production costs, substantial reduction in output energy and production value restricts its suitability. For any given core experiment, among undersowing treatments, WC seems more reliable option than BM, compared with N_{us}, in terms of energy input and output, energy productivity, price premium, gross margin and benefit to cost ratio.

Previous studies have reported considerable benefits related to soil and environment with cover crops in reduced tillage settings (Holland 2004; Tilman *et al.* 2002). Furthermore, wider energy or economic impact of various husbandry practices (for example benefits of carbon storage, reduced water runoff, etc.) has not been considered. Hence, to assess sustainability over a longer term between different husbandry techniques within the organic sector proper comparisons have to be made taking into account the wider benefits of agroecosystems, as stated by Tiziano *et al.* (2011).

Chapter – 7

GENERAL DISCUSSION AND CONCLUSIONS

7.1 Introduction

Conventional agriculture practices are considered to reflect higher-input industrial agriculture (Pretty 2005). In this context, the main aim is to make efficient use of renewable and non-renewable resources on a global scale without considering future needs that are not anticipated by the economic systems (Bergkvist 2003). In contrast, organic agriculture reflects more ecological principles, to make more efficient use of local resources and increase productivity of a local ecosystem (Lampkin 2002). Organic agriculture intends to produce harvestable yields at about the same level as in conventional agriculture, but mimics the beneficial soil-building fertility and structural traits (Jackson 2002).

Until very recently, it was thought that the production of all crops (conventional or organic) must involve the use of some degree of cultivation, ranging from the simple (involving either digging or punching holes to sow seeds) to the highly complex, involving primary tillage followed by secondary cultivation with different machines and equipment (Lal 2007; Schjonning & Rasmussen 2000). Regardless of whether it is done using a hoe or machines, tillage invariably cuts, loosens and in some case, mixes and inverts the soil (Brassington 1986). Inappropriate or excessive long term conventional cultivations reportedly have negative impacts on soil quality (Greenland 1981; Holland 2004). Among the disadvantages previously observed are land degradation, compaction of soil below the depth of tillage, increased susceptibility to water, wind and soil erosion and accelerated decomposition of soil organic matter (Unger *et al.* 1973; Blevins & Frye 1993). For these deleterious effects on soil structure, a number of reports (Derpsch *et al.* 2010; Carter *et al.* 2003a; Holland 2004) during the last decade questioned the use of conventional tillage. To potentially address, the recent trend have many developed countries has been to replace conventional tillage with non-inversion tillage systems. Non-inversion tillage systems are reportedly thought to reduce the detrimental effects of soil degradation processes (Halvorson *et al.* 2002; Vakali *et al.*

2011). However, some researchers still believe that conventional tillage has beneficial effects on crop production due in part of weed control, loosening compacted soils and for yield security (Morris *et al.* 2010). But others believe that by pulverising and inverting soil tillage in the long run does more harm than good to soils and should therefore be discontinued (Lal 2007). Both differences in these thoughts have some experimental evidence to support their arguments.

Environmental concerns have also encouraged the development of practices that require less use of chemicals to conserve soil fertility (Fageria 2009). Crops included in this manner are called cover, catch, or green manure crops (Bergkvist 2003). Previous studies have reported numerous benefits accrued by use of cover crops including: reduced, or sometimes eliminated the need of synthetic nitrogen; suppress weeds; reduced soil erosion; improved soil aggregation, and water retention (Hartwig & Ammon 2002). However, diversified cropping systems are reportedly difficult to manage and some studies have also shown that cover crops are not reliable enough to replace synthetic chemicals or mineral fertilisers (Cavigelli *et al.* 2009; Taylor *et al.* 2001; Berkvist *et al.* 2011).

Taking all these views into consideration, the main objective of this research is to find a suitable tillage systems and legume cover crops for organic wheat production in a given soil and local environment. The core experiments (I, II and III) demonstrated the influence of contrasting multi-tooled tillage techniques from full inversion to low or high residue non-inversion tillage systems, and also undersowing with either white clover or black medic legume cover crops on winter and spring wheat performance, in the absence of synthetic inputs. Within the organic sector, the potential importance of these important cereal crops is high, but field-trial performance was sometimes inconsistent in relation to yield (and protein content) in the seasons studied. The study objectives may be clarified by the following discussion:

7.2 Cultivation systems and wheat performance

The key findings from all the core experiments (I, II and III) were listed in Table 7.1. Seedbed preparation is critical for any farming systems (organic or conventional), as it determines crop emergence, growth and ultimately yields (Atkinson *et al.* 2007).

Table 7.1 Key outcome for the study period 2010 – 2013

	Conventional tillage (CT)	Low residue non-inversion tillage (LRNiT)	High residue non-inversion tillage (HRNiT)
Tillage intensity	High	Medium	Low
Seedbed	Fine	Coarser	Much coarser
Condition	Level/ uniform	Variable/non-uniform	Highly non-uniform/increased variability
Soil resistance	Low	✶Comparable	High
Wheat establishment	High	Intermediate	Low
Ear numbers	High	✿Comparable/Intermediate	Low
Thousand grain weights	High	✿Comparable/Intermediate	Low
Final grain yield	High	✿Comparable/Intermediate	Low
Disease pressure	✦Low	✦High	✦High

✶*Statistically comparable with CT (Chapter 3 and 4)*
✿*Statistically comparable with CT only for winter wheat in 2010/11(Chapter 2), statistically intermediate for spring wheat in 2012 and 2013(Chapter 3and 4)*
✦ *Only observed in 2012 season (Chapter 3)*

Troeh *et al.* (2004) reported that a soil with high clay content and poor tilth can form hard clods which can possibly hinder crop production and sometimes also increases both power and fuel requirements. Considering the clay soil texture and assumption of increased seed-soil contact, it appeared that mouldboard ploughing and power harrowing (CT) improved soil conditions and crop emergence consistently in the seasons studied. This is likely due to hard, cloddy, and massive structure of clay soils, with the passing of the power harrow breaking down the massive structure into loose fine tilth (Comia *et al.* 1994; Vijaya Bhaskar *et al.* 2013a). In contrast, two pass + drill

(LRNiT) and one pass + drill (HRNiT) without soil inversion and with clayey soil does not seem to provide optimal seedbed conditions to that of CT for crop emergence (Vijaya Bhaskar *et al.* 2013a). Implying that as the number of passes reduced and soil surface residues increased, the seedbed conditions tend to be much coarser with large and thick soil clods affecting seed-soil contact or perhaps drill performance (blockage), thereby resulting in lower seedling germination (Siemens & Wilkins 2006).

For any farming system, successful crop production depends highly on seed emergence and a uniform plant stand. Previous studies have often indicated positive relationship between crop yields and plant establishment, and its subsequent yield contributors (Ghaderi *et al.* 2009). Accordingly, in this study, CT that had significantly higher plant establishment also resulted in greater or compare favourably in terms of grain yield. Although, transition to LRNiT had statistically non-significant effect on yield to that of CT during winter wheat growing season in 2010/11, it substantially reduced yield in the subsequent spring wheat cropping season in 2012 and 2013. Transition to HRNiT significantly reduced yield contributing components and grain yield under all investigated core experiments compared with LRNiT or CT. Various reasons have been attributed to the lower crop performance under non-inversion tillage systems, compared with CT in each corresponding experiment (Chapter 2, 3 and 4). Nevertheless, in the seasons studied (in particular, cooler and wetter season – core experiment II) it was evident that the wheat production under non-inversion tillage systems is the result of complex interaction of a number of factors including seedbed variability, moisture status, crop adaptability to stress and varying environment, weed competition and disease pressure (Table 7.1). This situation making it difficult to confined the influence to one likely yield limiting factor.

In general, the transition to non-inversion tillage systems may provide more challenging seedbed environment for the main crop right from seeding, supporting Nielsen *et al.* (2006). In addition, numerous other factors including weather conditions, variability in crop growth, disease pressure and weeds competition were also found to interact more negatively and modify crop performance to a greater extent under non-inversion tillage systems. Most of the positive effects under non-inversion tillage systems (in assisting crop performance), for instance greater soil moisture retention during dry spells (core experiment III), increase in earthworm numbers (Chapter 3 and 4) and improved soil organic carbon, and nitrogen content (Chapter 3 and 4) may possibly have restricted or been compensated because of stressed and poor phytosanitary habitat (relative to weeds or disease pressure). Conventional tillage although, has been questioned in recent years, the success of non-inversion tillage seems strongly linked to specific environmental conditions, supporting the reports of Holland (2004); Peigne *et al.* (2007) and Morris *et al.* (2010). The success of conservation tillage in arid, semi-arid, and tropical regions is widely reported (Murphy *et al.* 2007; Lal 2007; Unger *et al.* 1991; Celik *et al.* 2011; Lawrence *et al.* 1994; Rasmussen *et al.* 1998; Galantini *et al.* 2000). Studies in temperate regions also reported some success. However; the results are mostly under lower rainfall conditions (De Vita *et al.* 2007; Martinez *et al.* 2008; Arshad *et al.* 1999; Bonfil *et al.* 1999) or with the use of higher synthetic inputs (Carr *et al.* 2013; Kong *et al.* 2009).

Wheat performance and productivity was one of the central objectives that the current research focussed on. Considering factors such as seedbed variability and complexity, and climate uncertainty like many previous reports (Morris *et al.* 2010; Stoate *et al.* 2009; Stagnari *et al.* 2009) this study also regards that conventional tillage (CT) has the highest potential to present reliable organic crop field and yield performance in a given soil and location. Among non-inversion tillage systems practiced, it seems that LRNiT has the utmost potential to be considered as a transition practice for CT, provided better seed-soil contact. It is not so surprising that in these varying climatic conditions, crop performance were greatly and negatively affected under HRNiT.

7.3 Cultivation systems and weeds

The key findings from all the core experiments (I, II and III) were listed in Table 7.2. Regardless of cultivation treatments, highest crop growth and crop yield was always obtained when weed infestation was lowest in the season studied.

Table 7.2 Trends in weeds biomass for the seasons studied 2010-2013

	CT	LRNiT	HRNiT
Early total weeds	Low	Statistically comparable with CT	High
Weeds prevalence for each growing season (Phase II to final harvest)	Low	Statistically comparable with CT	High
Broadleaf weeds	High	✿Intermediate	Low
Grass weeds	Low	✿Intermediate	High

✿ *No consistent trend observed in the seasons studied, mostly comparable (statistically) with CT or statistically intermediate between CT and HRNiT*

Variation in seedbed conditions had an overriding effect not only on crop emergence but also on the DM of broadleaf and grass weeds, and therefore total weeds. In the seasons studied, more tillage intensity had significantly lower total weeds, compared with maximum reduction in tillage intensity such as HRNiT. This result is in line with many previous studies (Clements *et al.* 1996a; Hakansson 2003; Froud-Williams *et al.* 1983a). As with the previous studies of Teasdale *et al.* (1991); Froud-Williams *et al.* (1983b), although, more levels of tillage with CT and LRNiT reportedly promote weed germination, the subsequent tillage in each season then destroyed the weed seedlings. This condition resulted in lower weed environment earlier in the growing season. Furthermore, increased cultivations that can potentially increase soil mineralisation rate (investigated in Chapter 3 and 4) also possibly favour the primary crop by providing a head-start relative to other weed emergence.

Previous studies often reports that the competitive effect of weeds on a wheat crop is critical before the end of tillering phase; the most relevant period of yield formation (Bergkvist 2003; Wilson *et al.* 1985). Gooding & Davies (1997) reported that competition of weeds is also more likely to increase shoot mortality. Although, total weeds were significantly higher with HRNiT, compared with CT or LRNiT in each season during the end of tillering phase, the tillering pattern seems unaffected, despite tiller numbers varying among cultivation treatments (Chapter 2, 3 and 4). Moreover, the shoot mortality rate ((maximum shoots - ear numbers)/maximum shoots *100) also appeared to be comparatively less with non-inversion tillage systems to that of CT in the seasons studied. This situation make it difficult to describe whether, increased weeds prevalence alone had any effect on the primary crop, without considering other factors (for instance seedbed variability, variation in plant establishment, crop growth rate and its competitive ability). Furthermore, in each season, there was no significant effect of increased weeds prevalence on wheat N%, although, total wheat nitrogen uptake (as a result of wheat biomass differences) showed significant tillage effects. Gooding & Davies (1997) reported that when a crop is in competition with weeds for nitrogen it would be expected to have detrimental effects on the crops recovery of nitrogen. Regardless of cultivation treatments, in this study, there was no clear evidence that weeds compete with the main crop. Despite being unable to understand the weed influence alone on early (and mid-season) crop performance, plant height, total wheat biomass and thousand grain weights is thought to provide some insight into the clarification of weed impact. Previous studies (Wilson *et al.* 1985; Moss 1987; Hoffman & Pallutt 1989) reported that greater weeds prevalence sometimes reduces crop vigour, grain weights, and grain numbers per ear. Nevertheless, as previously mentioned in each cropping year variations in climatic condition, crop type and difference in sowing date all hindered the investigation. Although, the core experiment (I, II and III) found that weeds competition may also be a probable reason for lower crop performance, further investigation is therefore needed to clarify its particular effects on the exact limitation for crop production.

Generally, compared to CT, both LRNiT and HRNiT in each season (particularly, during early growth phase) showed large variation relative to seedling emergence, early crop growth and weeds distribution. Although the results were consistently showing inverse relationship between crop performance and higher weeds prevalence (Chapter 2, 3 and 4) as reported in the literature (Clements *et al.* 1996a; Holland 2004) this study was unable to relate total weeds effect alone as a yield limiting factor. This condition, however, seems not to be unusual, as other studies also failed to assert the weeds effects alone as a yield limiting factor. In the stockless rotation trials of Bulson *et al.* (1996) wheat yields were significantly lower at higher weeds dry matter, although whether weeds alone were a cause of reduced yields or simply the symptom of poorly competitive crop could not be determined. This assertion was also supported by Clarke *et al.* (1999) who declared that even at relatively high weed density there was no evidence that weeds were competing with the main crop.

Among weed species, CT had significantly higher broadleaf weeds and HRNiT had significantly higher grass weeds. This observation was consistent in each season, confirming that the more often the soil is tilled, the greater is the emergence of broadleaf weeds, while the reverse occurred for grass weeds. These observations were similar to previous studies (Froud-Williams *et al.* 1983b; Gill & Arshad 1995; Holzner 1982; Locke *et al.* 2002; Hakansson 2003; Pareja & Staniforth 1985).

Many studies of tillage systems have demonstrated long term changes in the properties of top soil (Buhler 1995; Ball & Miller 1993). In the present study, as also seen with Streit *et al.* (2002) weed species appear to adapt quickly to changing soil conditions and thus the weed population differed significantly among the cultivation treatments, shortly after the onset of the contrasting cultivation experiment, perhaps before the composition of the soil seed bank could have markedly changed. For example, *Poa annua* (annual meadow grass) was initially not present but invaded non-inversion tillage plots shortly after the start of the trials (field observation). Furthermore, the practice of less tillage without inversion had adversely increased their population in each of the growing season. Unlike HRNiT, for more tilled soils, soil weed seed bank was not directly investigated as a result, the repeated occurrence of broadleaf weed species were unable to describe whether due to the carryover of non-dormant buried weed seeds, as reported by Pollard & Cussans (1981) or has occurred as a result of environmental condition or time of year, as generalised by Derksen *et al.* (1993). Additionally, the simplified cropping sequence might also be the added reason for not able to control the reoccurrence of specific weed species, as reported by Davies & Welsh (2002).

In general, if the focus lies just on weeds and cultivation systems, then this study like other studies (Hakansson 2003; Clements *et al.* 1996a; Swanton *et al.* 2000; Froud-William *et al.* 1983b) also showed that less tilled soils such as HRNiT had significantly higher total weeds and grass weeds, compared with more tilled soils.

7.4 Overwinter effects of legume cover crops

In organic farming conditions with more soil intensive tillage, the non-inversion tillage systems; the legume cover crops and lack of soil inversion are all considered to be a critical factor for possible weed control (Moore *et al.* 1994; Walters *et al.* 2008).

Regardless of cultivation systems, intense weed emergence during the ripening of the main crop may be potentially harmful to the following crop under any stockless-farming conditions (Welsh *et al.* 1999). This risk may be minimised by undersowing a legume cover crop. Such cover crops contribute to the controlling of the weeds during the time when the main crop is not present, and the time when the succeeding crop is thus far developed that it is able to suppress weeds on its own (Welsh *et al.* 1999; Hiltbrunner *et al.* 2007a). The cover crops reportedly develop faster relative to the weeds, which can possibly hamper the germination of weeds as the soil is quickly covered (Zink & Hurle 1990). Hence the successful control of weeds depends on biomass production and the early vigour of cover crops (Liebman & Dyck 1993). Additionally, cover crops in association reportedly interfere with weeds also through environmental modification, competition, physical impedance, and perhaps, allelopathy (Teasdale & Mohler 1993).

Overwinter assessment (2011 and 2012) was considered mainly to provide an insight into the carryover of residual effects under non-inversion tillage systems, to which wheat was being oversown in each season. The ability of legume cover crops that can quickly cover the ground, and prevent other weed emergence is thought to lower weeds competition for the succeeding crop (Unger & Vigil 1998).

Overwinter 2011 realised considerable growth of white clover (WC) and black medic (BM) legume cover crops (Chapter 3, core experiment- II). Ohlander *et al.* (1996) also reported that legume cover crops produced major part of their above-ground biomass during the post-harvest period. Among legume species, WC significantly had a higher legume DM than BM. This condition showed a more inverse relationship to that of weeds DM, compared with BM or non-undersown (N_{us}). Studies by Teasdale (1996) and Teasdale & Mohler (2000) reported that 2.7tha^{-1} to 7.0tha^{-1} of above ground cover crops dry matter can effectively suppress weed density of 75% to 80%. Compared with these results, it is not so surprising that an 80% increase in WC legume DM to that of

N_{us} may have reduced 15% weeds DM in a growing environment. In contrast, although BM legume DM (37%) was statistically higher than that of N_{us} there was no significant difference in weeds DM. Doring *et al.* (2013) and Squire (1997) also reported that BM showed no or reduced effect on weeds, that might be expected from its biomass.

Overwinter 2012 (Chapter 4, core experiment - III) however, had a different consequence. The climatic condition (overwinter 2012) was relatively similar to that of spring wheat 2012 growing season. Higher precipitation during autumn and overwinter (almost twice the amount of rainfall relative to overwinter 2011) appear to have favoured more weeds growth and ground coverage, despite the presence of competitive legume cover crops. Nevertheless, the ability of legumes to put on new growth seems to be rapidly taken up by these weedy conditions, and thereby reflect poor competitive ability of legume cover crops at higher weeds growth.

From these contrasting assessments, it appears that more vigorous growing legume cover crops in particular WC, can have the potential for weed control when weeds ground coverage is weak, or perhaps can prevent the germination of small seeded annual dicotyledonous species (despite, individual weed species not being directly studied) that require light to germinate (Teasdale *et al.* 1991). Nevertheless, at higher weeds ground coverage and at increased rainfall condition even competitive legume cover crops seem to be outcompeted by a vigorous weeds growth, supporting Biederbeck *et al.* (1996) and Nielsen & Vigil (2005). The overall observation supports previous studies (Kruidof *et al.* 2009; Walters *et al.* 2004) that cover crop systems may reduce some weeds. However, it may not be reliable enough to prevent weed populations increasing to severe field infestation levels in the longer term.

7.5 Legume cover crops effect on wheat yield and weeds

Restriction of herbicides is the main reason for the use of cover crops in organic farming systems (Hollander *et al.* 2007). Cover crops growth reduction, therefore, by chemical means is not an option. The major requirement for using cover crop with the main crop is reportedly for providing sufficient level of weed control and not having a strong negative effect on the growth of the main crop (Hollander *et al.* 2007).

Separating the growth of the main crop and cover crop has been advocated by sowing cover crop lately after the establishment of the primary crop to provide a head-start (Muller-Scharer & Potter 1991). This is a popular option often considered for organic conventional tillage (Carr *et al.* 2003). Ohlander *et al.* (1996) reported that undersowing of cover crops later in the growing season of main crop may reduce the competition with main crop, but it may also result in little weed suppression during the season of the main crop. Bergkvist (2003) also reported that delayed sowing of cover crop may be too late for them to have a positive effect on yield. In contrast, for non-inversion tillage systems, cover crop residual effects continues despite, addition of annual legumes by undersowing. To reduce early competition for wheat and to help with drilling, dense living residue were checked using either one pass (HRNiT) or two pass (LRNiT) tillage operation. However, Hiltbrunner *et al.* (2007a) reported that an increase in soil tillage intensity before/during wheat sowing to reduce the interference of surface residue may result in greater weed infestation due to poor competitive ability by recovering legumes.

The present study with contrasting cultivation treatments and difference in management (green manuring/bi-cropping) of legume cover crops made the investigation more difficult while making comparison. Furthermore, the non-undersown (N_{us}) subplots were also not completely free of legumes, due to natural regeneration of previous ley, which also hindered the overall investigation.

The growing of legumes in combination with cereal reportedly have potential weed control and yield advantages (Gooding *et al.* 1993; Jensen 1996) although, in general, these effects were not consistently observed in the seasons studied. During each season, the growth of legumes (residual or additional) was either favoured or highly restricted based on weather events in particular, precipitation patterns and also by weeds prevalence (as the study progressed). Accordingly, for winter wheat in 2010/11 (Chapter 2) and spring wheat in 2013 (Chapter 4) legumes had no significant effects on crop performance, probably, due to the above mentioned variables.

Only in the 2012 spring wheat growing season (Chapter 3, core experiment- II) the influence of legumes was more clearly observed due to increased rainfall. Among legume cover crops, the initial assessments (Phase I and II, based on biomass) suggested that WC had more vigorous growth than BM, although this difference was not statistically more pronounced at later stages (Phase III and final biological harvest). The early statistical difference in biomass between the legume cover crops is thought to have resulted in differences in their ability to deal with weeds. The ability of WC to establish quickly and to occupy the ground space faster showed significantly inverse relationship with broadleaf weeds and hence total weeds, compared with BM. Fisk *et al.* (2001) highlighted that the cover crops which are well established before weeds emergence, may possibly inhibit germination of short-lived annual weed species by reducing light interception. Clements & Donaldson (1997); Jones & Clements (1993) and Bergkvist (2003) also reported that white clover as cover crops or living mulch in small grain cereals showed positive broadleaf weeds suppression. In contrast, Clements *et al.* (1996b) and Teasdale (1996) reported that slow early vigour of cover crops (as with BM in this study) may help increase weed infestation, because weeds can quickly occupy uncovered patches. This condition may have resulted in significantly higher broadleaf weeds and total weeds, compared with WC, although, statistically comparable with $N_{us.}$ Compared to $N_{us,}$ neither legume cover crops had an effect on monocotyledonous grass weeds. This is not so surprising because soil tillage was practiced before/during wheat drilling and tillage would have possibly allowed grasses to regenerate and quickly cover the empty spaces before recovering of legumes or annual addition of legumes or wheat begins to successfully compete with them, as also reported by Hiltbrunner *et al.* (2007a).

Koefoed (1996) and Clements *et al.* (1996b) reported that cereal-legume intercropping results in reduced yield components and fewer grain yields than wheat alone due to greater competition from legumes and weeds. Similarly, reduced competitive ability of BM appears to increase non-wheat DM (legumes and weeds) in a growing environment. This situation might have significantly affected spring wheat performance resulting in fewer grain yields than $N_{us.}$ In contrast, WC legume DM showed an inverse relationship with weeds DM and might have limited competition in the growing environment for the main crop. Accordingly, there was no significant yield component or yield reduction observed to that of $N_{us.}$ Furthermore, the non-significant difference in wheat N concentration between undersowing treatments indicate that these techniques (annual addition for conventional tillage or oversowing cereal into checked residue) may not be an effective option. Hence other techniques need to be considered in order to improve the practicability of cover crops and tillage systems on such organic wheat production.

In general, if the focus lies on cereal-legume bi-cropping, then this study like Clements & Donaldson (1997) and Jones & Clements (1993) also regards that WC seems to be more reliable option than BM in terms of superior weed control and reduced negative effects for the cereal crop in the 2012 season studied.

7.6 Concluding remarks

Conventional cultivation presented either the equivalent or a highest grain yield than other cultivation treatments.

The plant establishment and its subsequent yield contributors (increase or decrease) with any cultivation treatments were positively related to grain yield.

Wheat production can be seriously affected where primary crop competitive ability is reduced due to seedbed variability.

More soil cultivations had inverse relationship with grass weeds and total weeds, while the reverse occurred for less tilled soils such as high residue non-inversion tillage.

White clover seems to be a more reliable legume cover crop to undersow due to its vigorous growth, more inverse relationship with broadleaf weeds and total weeds, and also less negative effects on spring wheat (2012).

Different cultivation regimes and legume cover crops had no impact on grain protein content.

In stockless organic farming, cultivation regimes and legume cover crops may not be the only reliable option to prevent weeds from growing to severe field infestation levels.

Chapter - 8

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Appendices

Appendix 1. Publications prepared during this investigation

Vijaya Bhaskar, A.V., Davies, W.P., Cannon, N.D. & Conway, J.S. (2013). Organic wheat performance following conventional and non-inversion tillage systems. *Biological Agriculture and Horticulture,* 29 (4), 236-243.

Vijaya Bhaskar, A.V., Cannon, N.D. & Davies, W.P. (2013). Investigation of suitable legume species for undersowing in organic spring wheat. *Rethinking Agricultural Systems in the UK, Aspects of Applied Biology 121*, 199-202.

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Vijaya Bhaskar, A.V., Davies, W.P., Cannon, N.D. & Conway, J.S. (2013). Characterisation of soil quality following conventional and non-inversion tillage for organic farming. *Rethinking Agricultural Systems in the UK, Aspects of Applied Biology 121*, 181-185.

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