HARPER ADAMS UNIVERSITY

Towards precision inputs through improved understanding of the underlying causes of in-field variation in lettuce crop maturity and yield

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By

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Declaration

This thesis was composed by me and is a record of work carried out by me on an original line of research. All sources of information are shown in the text and listed in the references. None of this work has been presented/accepted for the award of any other degree or diploma at any University.

Yara Boubou April 2018

Abstract

In-field variability in the yield of the mature lettuce heads affects the efficiency of a single-pass harvest. Heads that do not acquire the target weight range and quality at harvest result in crop wastage. Understanding the overall causes of this variability may inform targeted solutions for improving yield uniformity. Examining the potential for using current tools in precision farming, such as soil apparent electrical conductivity (ECa) scans and geographic information systems may help identifying the effects of soil heterogeneity on this variation. This in turn will support the making of precision management decisions.

The central hypothesis for this study was that there are underlying physiological and edaphic factors that control the spatial variability in lettuce fields. Five field experiments and four glasshouse experiments were conducted between 2014 and 2017. Scans of ECa identified field zones of difference in both yield and soil. Zones varied statistically in clay content, magnesium, potassium, phosphorus, as well as, plant fresh weights 35 days after planting and at harvest. However, the underlying variation in ECa did not explain this difference. Grid sampling studies showed that lettuce yield varied spatially but not seasonally, and that bulk density was the strongest predictor for lettuce yield for two successive crops. The results of field studies suggest that in-field variation in lettuce yield is mainly derived by soil type and soil physical properties such as bulk density, the mineral fraction of the soil texture, organic matter and soil profile.

Glasshouse studies explored the effect of transplant dissimilarities on the variation in plant growth after transplanting. Transplant weights and sizes varied considerably within trays and this variation amplified 14 days after planting. Furthermore, variations in transplant orientations and depth at transplanting affected significantly the quality and the quantity of the final yield. Glasshouse studies suggest that a considerable proportion of the variation in lettuce yield is a result of dissimilarity in transplant sizes at the propagation stage and farming practices during transplanting.

ECa scans helped identifying different soil zones within the studied field and enabled targeted soil sampling which revealed significant variations in soil properties and lettuce yield. Variable field zones could be identified using soil EC scans, maps of soil properties, as well as the yield maps. Field areas that varied in EC ranges varied statistically in soil texture and major nutrients. And whilst lettuce yield in this study varied spatially and not temporally. It was also found that there is a proportion of the variation in lettuce yield starting at early stages of growth, before and at the transplanting in the field. Bulk density was the strongest predictor for both yields of lettuce. The suggested role for organic matter in the variability of the yield was supported by the glasshouse experiments.

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Dedication:

To the kids I used to play with in the neighbourhood when I was little, but we did not manage to grow old together. To the kites, the mud, the rain puddles and paper boats. To Ayman, the boy next door, in heaven.

Published work

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1 Literature review

1.1 Introduction

The purpose of conducting this research was to improve our understanding of the overall causes of in-field variation in lettuce crop, due to the effect of this variability on the harvest efficiency for the growers they wish to harvest heads of a uniform size and weight in a single pass. This was done in the context of supporting variable management decisions making to increase marketable yields through reducing this variability.

Lettuce growth is influenced by soil properties, climatic conditions and agricultural practices as well as the interactions amongst these three factors. Understanding the spatial variation of these factors is fundamental when assessing the spatial distribution of crop yields and soil properties for making precision farming decisions. Furthermore, variability in the growth of lettuce transplants leads to variation in head weight and maturity at harvest and can affect post-harvest quality

Geographical information systems and spatial data collection have recently become significant in field studies, representing promising cost-effective tools for putting precision farming into practice. Although agriculture has been striving for greater uniformity of production for centuries the term ‘Precision agriculture’ has become synonymous with farming with the aid of Global Navigation Satellite System (GNSS) which became, available in the 1990’s. Similarly, the growth and development of computerised geographical information systems (GIS) and detailed field mapping with electrical conductivity (ECa) has made in-field soil and crop variation both identifiable and quantifiable.   However, most of the research undertaken was done on long season crops such as cereals and very little on short season crops such as lettuce, despite some of this research had focused on variable water supply lettuce and variability in soil water properties within a field for lettuce. One study was found that attempted underpinning the relationship between lettuce and soil factors in a salinized field through comparing several geostatistical approaches to optimise lettuce yield. Research into variable crop management in Lettuce and precision farming application of relevance will be discussed.

1.2 The lettuce crop

1.2.1 Lettuce (*Lactuca sativa*); taxonomy, physiology and morphology

Lettuce is classified as a crop for temperate zones with cool weather (Wurr et al., 1992). Commercially grown lettuce is categorised into four groups; crisphead (Iceberg), butterhead, leaf lettuce, and Cos (Romaine). Of these, iceberg is the most commonly grown (Ryder, 1999).   Lettuce seeds are inseparable achenes, thin small and dry that germinate after water imbibition. Seed emergence is known to be variable due to two dormancy phenomena: "Thermo-dormancy" which occurs when the seeds are exposed to temperature higher than 30° C during the water absorption stage, and "Skoto-dormancy" which occurs when seeds are exposed to darkness. The rooting system in lettuce is relatively shallow, consists of a short taproot that grows up to 60 cm or sometimes longer, with cross roots that are most densely situated on the upper part of the taproot (Jackson, 1995 and Johnson et al., 2000). Hence, most of nutrients and moisture exploitation is concentrated in the upper level of the soil. Emerging seedlings produce increasingly-broadening leaves, one after another on a shortened stem forming a rosette of leaves. The rosette structure continues developing all through the vegetative life of the plant in leaf lettuce or forms the head in Crisphead types. The head-forming or hearting stage (heading in U.S) happens as a sequence of changes in the orientation and morphology of the leaves, where the leaves become more erect and curved (Figure 1.1). The leaves then overlap closely on top of the growing apex of the stem, forming the iceberg head. Simultaneously, the leaves broaden and the leaf-midrib arches inwards. At the reproductive stage, lettuce tends to develop an elongated stem towards the end of the vegetative growth (Jackson, 1995 ; Wein, 1997 and Ryder, 1999).

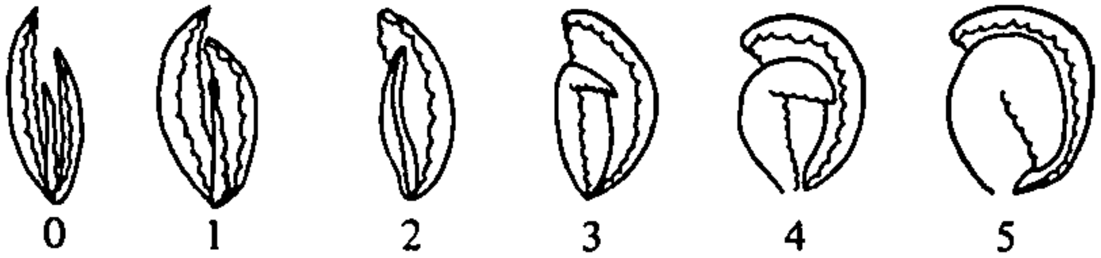


Figure 1.1: The change in leaf morphology and growth during the heart forming stage in Iceberg lettuce head. (Source: Wurr et al., 1987)

1.2.2 Lettuce in the industry

The utilised area for agricultural production in the UK is estimated to be 17.5 million ha, which forms up to 71 % of the total UK area. Horticultural crops occupy over 167000 ha of this production, of which 140000 ha of horticultural crops in England with 96000 ha of vegetables grown for human consumption (The Department for Environment, Food and Rural Affairs (Defra) statistics, 2017). In 2015, the value of fresh vegetables produced in the UK was estimated to be £ 1.3 billion, which contributed to 57 % of the total UK supply. The production of field vegetables in 2015 reached 2.5 million tonnes and the value of this production was estimated to be £ 885 million. The value of lettuce production was £ 17 million with over 13 thousand tonnes produced in the UK. The exports value of lettuces reached £13 million in 2015 (Defra statistics, 2016).

1.2.3 Commercial growing practices

The production cycle takes around 55 - 65 days depending on the climate of the production region (Ryder, 1999). The duration depends on temperature and solar radiation. Commercially, growing lettuce from transplants (Figure 1.2) is preferred to seeding. Using transplants saves time and ensures an optimum light interception at a minimum time especially if lettuce was transplanted at close spacing whereas direct seeding is less efficient, mainly due to the dormancy phenomena and adds additional costs for processes like thinning and seed coating (Wein, 1997). Moreover, the time of maturity is easier to predict when production is initiated from transplants, due to the variability in predicting seed emergence (Wurr et al., 1984). The need for developing modules and peat blocks for plant raising for the modern transplanting systems has risen since early 1980's, where applied research decreased the size of both peat blocks and modules to the extent where production from transplants became more economic than producing crops from bare-root seedlings grown in seed beds, in addition to the significant reduction in transplant failure and improved crop establishment and yield (Grey, 1986). The modules were initially more widespread and preferred to peat blocks, particularly pyramid shaped modules, as (Cox, 1984b) showed that this shape gave the highest shoot weight for both lettuce and leeks at planting in comparison to cylinder, cube and inverted pyramid shapes although he did not show and any effects for the module shapes on root growth. Moreover, the key components in module substrate are compost, sphagnum peat and sand with a range of ratios. These materials provided better environment for the growth and development of transplant roots in comparison with peat blocks and allowed a larger number of transplants to be established per unit area (Grey, 1986)

The use of peat block transplanting of vegetable has been developed in France and has been widely used in Western Europe. Key combination is brown peat that is moulded into cubes (Maltais et al., 2008). A major advantage with peat blocks compared with modules was that they retain their shapes throughout transplanting period, allowing for the transplanting of much younger plants that are needed for modules, and reducing the transplanting shock. In peat blocks there is no need for roots to fully exploit the entire volume of the substrate for planting to be possible (Maltais et al., 2008), unlike in modules where growers wait until the root exploit the entire volume of the module cell before planting in the field, where the compost of modules scatter much easier than the blocks and the main reliance is on the root in the cell to hold the compost. Limitations and disadvantages they are associated with the use of blocks made out of peat is that peat shrinks when dry resulting in partial loss of contact between the block and the surrounding soil that the block will gradually dry and the transplants will be exposed to water stress and die if these conditions occurred before the seedling was able to extend roots into the surrounding soil (Cox, 1984a). Cox showed that soil is unable to provide the plants with water immediately after planting and for few days after planting and that blocks in wet but not saturated soil are not always able to absorb moisture adequately in time to meet the plant needs (Cox, 1984). Moreover, recent environmental pressure on the restoration of damaged peat bogs, and on reducing the extraction of peat for agriculture (Lunt et al., 2010) is on increase and the demand for peat alternatives will add up further challenge for growers to find alternatives in the near future.

Figure 1.2. Iceberg lettuce transplant (Source: Kuack and Rapaka, 2011)

1.2.4 Propagation conditions:

The majority of field grown Iceberg lettuce have been established from transplants, which are grown under controlled conditions or protection since 1980’s (Wurr et al., 1987). Lettuce seeds are planted mechanically in peat blocks, one seed per block (Figure 1.3). The commonly used dimensions for blocks are 3.8 x 3.8 x 3.8 cm in summer, when plants grow fast. Smaller size blocks can be used when cropping under cooler weather conditions due to the slow growth of plants. The blocks are held inside multicellular trays that hold the young plants from seeding up until arriving at the field. Whilst propagation practices vary between producers the main processes are as follows. Trays containing 176 peat-based blocks (11 rows and 16 columns) with recessed central indentations (Figure 1.4) are seeded, the blocks are covered with a layer of horticultural sand to preserve moisture. The seeded trays are then transferred into a temperature-controlled germination room at 16 °C and high humidity from one to three days. This is followed by approximately 17 days of propagation in a temperature-controlled glasshouse compartment at around 18°C. After approximately 20 days the transplants are moved to the final compartment before the field stage. Whilst in the glasshouse, the trays are irrigated throughout glasshouse growth following standard commercial practice, receiving about 800 ml / tray per day (Elzbieta Witkowska Pers comm (G's Growers), 2015).

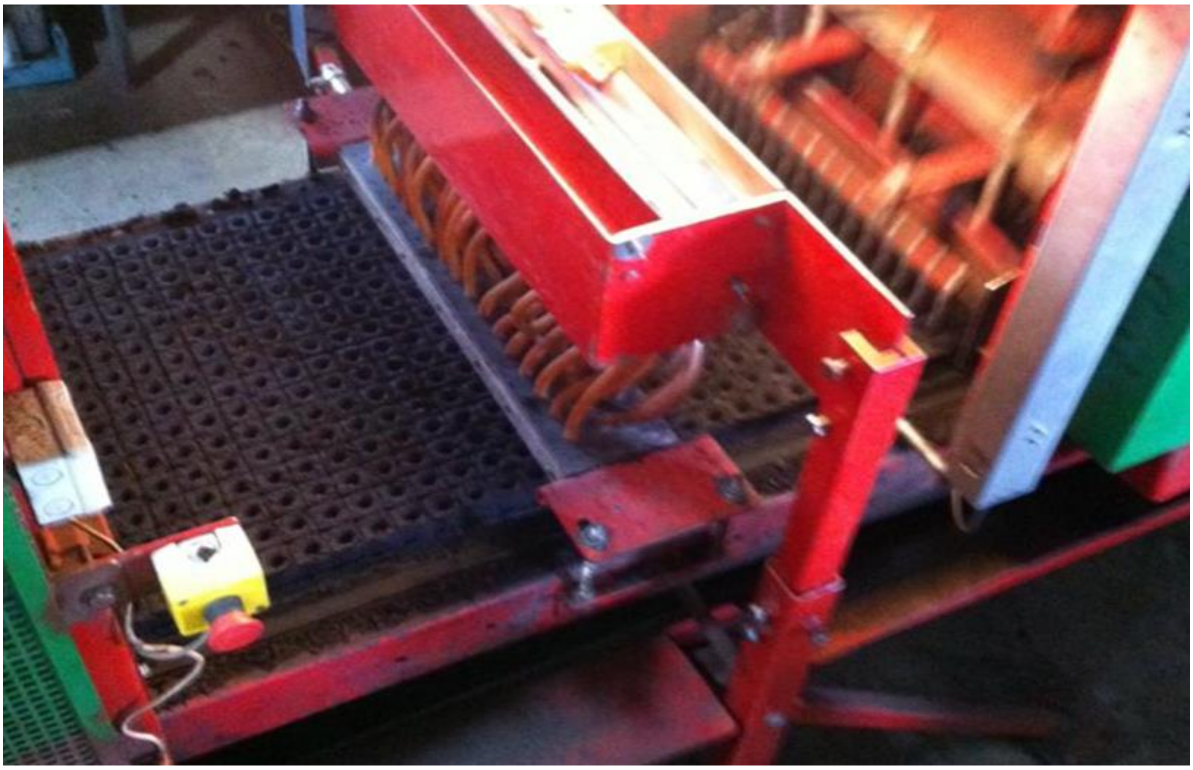


Figure 1.3: Mechanical seed planter, Second Willow Nursery, G's Growers Ltd, Littleport, Cambridgeshire, 2016.

Figure 1.4: Trays of transplants (20 days old) in a glasshouse compartment, Second Willow Nursery, G’s growers Ltd, Littleport, Cambridgeshire, 2016.

1.2.5 Transplanting:

Mechanical planters are used to place the transplants at approximately 1.5 cm depth and at regular spacing; 30 x 30 cm in early season and 30 x 34 cm in the warm season (late season) where plants grow and develop a larger crop surface area faster than in early season or cooler months. The peat blocks are also irrigated before transplanting and the irrigation water is also provided immediately after transplanting to encourage the establishment of the young plants. Cox (1984) suggested that lost moisture by evapotranspiration from the peat blocks must be replaced by water from the reserved moisture inside the peat blocks after planting until the roots have grown into the surrounding soil. Cox also demonstrated that the water movement in the soil and between the soil and peat blocks depends on water potential gradient of the soil and its hydraulic conductivity, which in turns depends on its water content (Cox, 1984). This reaffirms the importance of irrigating the peat blocks before planting and irrigating the transplants immediately after transplanting to ensure enough free water to surround the peat blocks and that encourages the growth of the roots outside the blocks. Manual adjustments for dead or damaged transplants follow the mechanical planting (Figure 1.5)

Figure 1.5. Mechanical transplanter at G’s growers Ltd, Cambridgeshire 2014.

1.2.6 Quality requirements and variability in Iceberg lettuce heads:

Lettuce is a crop of high perishability rate with a shelf life that ranges between 2 to 4 weeks (Kader, 2002). Lettuce is a source for vitamins and fibre in a healthy human diet. Whilst growers wish to achieve high yield with the highest possible marketable quality, consumers also demand high nutritional value of the produce (Sorensen et al., 1992). Moreover, growers are expected to consistently supply supermarkets with predictable volumes of the produce (Wurr et al., 1987) A high pressure therefore, is put at the growers to achieve this balance. In terms of the yield, lettuce trimmed heads of certain sizes and density (weights) are the target yield for growers; the weight target for Iceberg trimmed head ranges between 400 g / head to 800 g / head depending on supermarket demand and season i.e speed of growth. Meanwhile, to assess head density (in field conditions), the head is assessed by firmness under hand pressure which is normally done by the lettuce cutter. Head size and density are considered the most important maturity indicators and characteristics in Iceberg lettuce (Kader, 2002 and Jenni and Bourgois, 2008) in addition to the use of sowing date as a predictor of the maturity date (Wurr et al, 1984). Lettuce head maturity is important due to its effect on tissue stiffness and strength, and density determines the yield as denser heads of the same size and harvest date mean higher weight and yield (Newman et al., 2005). Head size however, could be less reliable as a maturity indicator if the closed heads did not form a certain density (entrapped leaves) inside. Growers commonly depend on both head size and head firmness to decide readiness for harvest (Jenni and Bourgeois, 2008). Some defects like bolting, leaf scorch, ribbiness and low head-density may occur during crop growth and development and these are non-desirable characteristics for marketing. These defects reduce the yield, the marketable quality and may also result in rejection of the produce by supermarkets or other clients across the supply chain. Jenni and Bourgeois, 2008 Quebec, Canada compared the precision of three methods for measuring head density in Iceberg lettuce as a maturity indicator. Differently to Gallardo et al*.,* (1996) and Luna et al*.,* (2012), where the later study assessed maturity by comparing heads from all treatments to the heads harvested from the control treatment; all heads were harvested when the heads from the control treatment became mature as indicated by the head weight (600 g) and degree of compactness which was scored based on a 1 to 8. The methods compared in Jenni and Bourgeois, 2008 study were; head density quantified by water displacement, head firmness assessed by hand compression and head density based on head weight and calculating volume using the equatorial and the polar diameters.

They measured head volume by water displacement and head firmness was assessed by trained evaluators that ranked the firmness of the heads under hand compression from 1 (soft) to 5 (extra hard or over mature). They found that assessing head density by head firmness method to have a better accuracy in comparison with head density estimated from measuring the head diameters. However, they recommended both methods for use by growers to better determining commercial maturity for crisphead lettuce. A limitation for this study is that the same heads were used for the three assessments and it was not clear which method was done first and how each treatment could affect the firmness of the head for the following assessment. Additionally, measuring 2-3 diameters in field situations to calculate volumes, and carrying out weighing the heads to again calculate density, might not be efficient for growers to be done on a large-scale production.

Both Newman et al., 2005 and Luna et al., 2012 reported that agronomic inputs and post-harvest storage conditions have the main impacts on the marketable and postharvest quality of lettuce; such as resistance to damage during processing in the salad factories and shelf life. Newman *et al.* (2005) tested the effect of postharvest storage humidity along with several agronomic factors including nitrogen, calcium on the mechanical properties of lettuce leaves. They found that the strength and the stiffness of leaves decreased in the plants grown with 120 kg / ha nitrogen application in comparison with leaves from lettuce heads grown without added nitrogen fertilizers. Both parameters increased in plants grown with added calcium. They also found an association between the decline in stiffness with wilting or reduced turgor, as well as, between greater turgid tissue and the susceptibility to cracking during processing.

1.2.7 Harvesting lettuces

Lettuce heads that are grown in summer-grown crop (June, July and August) are around 55 days old when they are harvested (from transplanting to maturity and harvest) and around 65 days old in winter-grown crop (March, April and May). Lettuce is manually harvested due to the sensitivity of this crop to handling and mechanical damage (Ryder, 1999 and Titley *et al*., 2007). The growers harvest lettuce in a single pass relying on both mobile harvest rigs and trained harvest workers (Figures 1.6 and 1.7) who cut the whole head, remove the outer loose leaves, trim the excessive stem and place the head on to a moving belt on the harvest rigs. The heads are normally packed onsite by wrapping in plastic film. They are then transferred into the transport trays or crates for one or sometimes two supermarkets at the same time. The number of heads per tray (commonly 10 or 12 heads per tray) depends on the supermarket request which in turn determines the size of the heads harvested (small vs large). Therefore, the trained harvesters aim for heads that are within the harvestable range (400 - 800 g / head). All the heads that are outside this range (underdeveloped or oversized) are not harvested and considered crop wastage (Rob Parker (G’s Growers) Pers Comm, 2015). From this perspective, variable head sizes and weights is a significant issue for head lettuce growers due to its effect on harvest efficiency and the final (marketable) yield.

Figure 1.6: Lettuce harvest rig during harvest, G’s Growers Ltd, Cambridgeshire. 2016.

Figure 1.7: Trimmed and wrapped lettuce heads ready to be transported.

1.3 The factors that affect field-grown lettuce yield (head formation)

Physiologically, successful head forming requires a slow rate of stem elongation, high rate of leaf production and large individual leaves (Wein, 1997). The hearting process in crisphead lettuce has been studied considerably, and in particular the relationship between head-formation and light and temperature (Bensink, 1971; Wurr and Fellows, 1991; Wurr et al., 1992; Wein, 1997; Ryder, 1999). Researchers agree that the leaf-shape, stem-length, growth rate and initial-growth speed are the key morphological aspects that determine lettuce yield (Bensink, 1971; Wurr and Fellows, 1992; Wurr et al., 1992; Wein, 1997; Ryder, 1999; Kader, 2002). Both Wein (1997) and Ryder (1999) suggested that the morphological changes that drive the hearting process could be the change in leaf width / length ratio, the production of leaves that have a cup shape or the arching of the distal leaf creating an outer cover for the new leaves that develop in the centre, forming a lettuce head (Wein, 1997 and Ryder, 1999).

1.3.1 Effect of solar radiation

The hearting stage is the main stage when lettuce crop is particularly sensitive to solar radiation and when adequate photosynthesis is particularly important for the rapid leaf development that occurs during this stage (Wurr et al., 1987)
Wurr and Fellows (1983) examined the effect of 12 sowing dates on the growth and development of three crisphead lettuce and reported an increase in emergence rate with the increase of the average soil temperature, and a linear relation between the number of

formed leaves and the ambient air temperature measured as accumulated day-degrees. Head weight was found to be significantly associated with the mean temperature for up to 42 days after seed emergence. However, they found no effect for solar radiation on head weight at maturity but on the time to maturity and they suggested that once the hearting process had begun, higher levels of solar radiation can shorten the time to maturity and promote fast filling for the frame leaves (the heart).

Wurr *et al* (1987) grew transplants of variable ages under variable day and night temperatures between 1984 and 1986 to examine the effect of raising conditions and transplant ages on the duration to maturity and head weight. They found significant positive correlation between lettuce head weights at maturity and the total solar radiation during the 10 days before 50 % of the hearting process has happened. They suggested that radiation became less relevant after the hearting has occurred, where the combination of radiation and temperature had small but important effect. However, they did not quantity the age of the plants at hearting or at 50 % hearting stage. They resorted to estimating the hearting time by taking weekly samples around the hearting stage where daily samples would have given better accuracy for the estimation. Wurr and Fellows (1991) then carried out another five field experiments between 1986 and 1987 where they observed significant correlation between head weight and the mean solar radiation in the period the extends from five days before hearting to 11 days after hearting. In this set of experiments, using 4 treatments they compared plants that were unshaded or shaded for different periods of time (Wurr and Fellows, 1991). However, in this case they did not essentially measure the light intensity as much as they measured the effect of the presence or the absence of shading. Therefore, it was not clear whether the difference in head weight was due to different level of shading or due to lack of photosynthesis in general that different levels of shading might mean different light intensities and photosynthesis, which affects the growth and the dry matter building of the plants.

1.3.2 Effect of temperature

The effect of temperature was confounded with the influence of solar radiation, in the field studies cited earlier. Not only is photosynthesis a heat sensitive process in all plants but also cell differentiation and expansion are temperature-dependent processes (Scaife and Aikman, 1996). Wurr and Fellows in their studies (1983), found a significant (negative) correlation between final head weight and the mean temperature during the period that extends from 13 days before hearting and up to 10 days after hearting. Wurr *et al* (1987), found that low temperature during early stages of growth is likely to cause a delay in hearting stage in comparison with crops that had received higher temperatures. And thus, they explained the seasonal variation in head weights. They also suggested that the main reason behind the variability between batches of transplants (transplants that are sown at different dates) in terms of ages and sizes, are the temperature and solar radiation, and noted that these two factors can vary greatly in commercial environments (Wurr *et al*., 1987). Similarly, Wurr and Fellows (1991) found that relative growth rate to be correlated positively with temperature during hearting (Wurr and Fellows, 1991).

The temperature that the lettuce roots are exposed to appear to have an effect on the crop resistant to high temperatures. Jie and Kong (1997) carried out a greenhouse experiment in Singapore to investigate the effects of the fluctuation in ambient temperature while cooling the root zone. Butterhead lettuce (*Lactuca sativa cv. Palma*) was grown in aeroponics under hot ambient day temperature that reached up to 41 C in June, while root was maintained at 20 C. they found that higher leaf temperature in the plants with uncooled roots resulted in lower photosynthesis function, whereas photosynthesis was higher in the plants that had their roots cooled down to 20 C. They suggested that the roots in temperate lettuce is the key to lettuce acclimation to higher ambient temperature and can help reduce the negative heat effect. However, they were unable to distinguish, in the case of damage in the control plants, whether the photoinhibition was a result of high temperature or water stress or the interaction between both factors.

Maltais *et al* (2008) grew Iceberg and Boston lettuce from seeds inside growth cabinets under two daytime temperatures 20 °C and 30 °C, where they measured chlorophyll content, biomass fresh and dry weight, leaf area and leaf length. They found great effect for temperature on Iceberg growth. The leaf area for Iceberg seedlings were 121 cm^2 under 30 °C in comparison with 90 cm^2 in the 20 °C cabinet. Leaf fresh weight and dry matter where increased by 42 % and 43 % respectively in the 30 °C growth cabinet compared to the 20 °C cabinet. The study did not show any difference in chlorophyll content or leaf length between the two temperatures. The limitation of these findings was that it was done in growth cabinets. And although the measured parameters were quantified effectively, these are difficult to transfer to field environment especially considering the great variability in UK. Wurr *et al* (1987) work suggested that from the beginning of May, establishing transplants under field conditions produces significantly heavier heads than those established under glasshouse conditions and he considered that as an explanation of why smaller transplants produced heavier heads although they take longer to mature. Wurr and Fellows (1991) summarised the ideal environmental conditions for heart formation as high solar radiation levels for a specific time just before and after hearting with low temperatures for a longer duration that lasts up until and during the hearting stage. Temperature variability across a field may also be influential on growth rate variability. Soil temperature may vary depending within a field depending on varied soil types and properties.

1.3.3 Effect of variety

Wurr and Fellows (1983) used three different American crisphead varieties and 12 sowing dates and concluded that lettuce response to environmental conditions largely depends on the varieties used. For example, cv Ithaca and Saladin responded oppositely to low temperature at early growth stages at the same sowing date where cv Ithaca acquired higher head weight than cv Saladin. This suggested that the difference in response could be due to the two varieties being bred for different purposes at two different places in the U.S. Similarly, Maltais *et al* (2008) noted that the Iceberg and Boston lettuce varieties they used in their studies responded differently to the different temperature treatments. Iceberg lettuce demonstrated higher growth rate in response to 30 °C ambient temperature in comparison to 20 °C whereas, Boston did not show a substantial difference in growth rate between the two treatments.

1.3.4 Effect of transplant size

During their investigation into the effect of solar radiation and temperature Wurr and Fellows (1983) and Wurr *et al* (1987) attempted to identify the effect of transplant ages and sizes by using a range of transplanting dates in the field which also meant varying the ambient conditions (Wurr *et al*., 1987) or by using variable sowing dates (Wurr and Fellows 1983). They observed that predicting the maturity of transplanted lettuce is more accurate than drilled lettuce due to the variability in emergence and the difficulty of establishment (Wurr and Fellows, 1983). They then related all variabilities in time to maturity and growth after emergence to temperature (98 % of the differences in growth were accounted for by temperature). Meanwhile, Wurr *et al* (1987) reported significant effect for the transplant age on the time to maturity, where 2 weeks old transplants matured later than the 3 to 4 weeks old transplants Wurr *et al* (1987) suggested that the time for which the transplants are held by the grower before placing in the field might affect the physiological status of these plants and the subsequent development which creates another factor that increases variation between batches of transplants. Moreover, they noted that a wide range of transplant sizes can mature successfully. However, the variability in the environmental conditions that accompany crop establishment and up until the hearting stage makes it difficult to determine the effect of sizes on the time to maturity and final head weight (Wurr *et al*., 1987). However, neither of the latter two studies clarified the direct effect of variability in plant sizes on the final head weight at harvest instead they suggested that it is the combination of the growth stage of transplant and the ambient conditions. Whilst, it was reported in other studies that both factors; the date of emergence and the size of transplants can have an impact of the final yield variability (Wurr and Fellows, 1984; Wurr *et al*., 1987; Harwood *et al*., 2010and Kerbiriou *et al*., 2013). Harwood *et al*., (2010) compared the coefficient of variations at early stages of growth to the coefficient of variation at maturity.

Furthermore, amongst these studies, Kerbiriou *et al*., 2013 was the only study that compared the effect of transplants variability under constant ambient conditions, where the effect of growing transplants of different sizes on the development and yield was investigated.

1.3.5 The effect of Soil texture, soil structure, nutrients and irrigation:

1.3.5.1 Soil structure

soil structure affects crop growth through its effects on root growth and nutrient uptake. The systems of pores and capillary tubes that the structure provide within the soil profile determines the dynamics of soil's air and water.

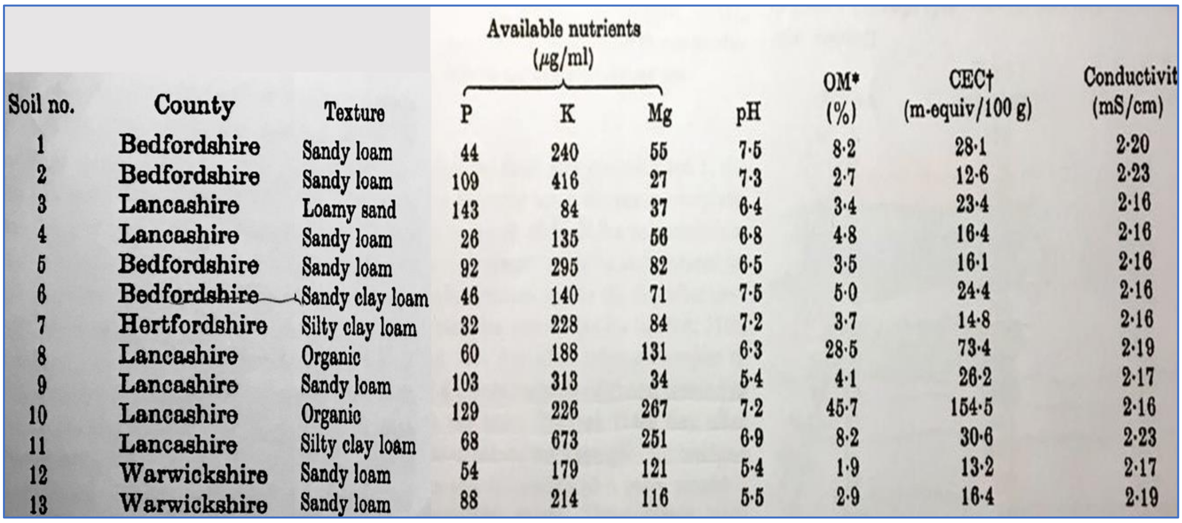
The available water content, bulk density, root penetration, aeration and drainage, all of these soil properties are largely influenced by the structure of the soil. Most of the soil water and nutrients are held in the fine pores (Davies *et al*., 1993). Light sandy soils and clay soils are the most susceptible to structural problems particularly under wetness or rainfall. That is due to excessive porosity in sandy soils which largely depends on the size of the sand particles, and the lack of porosity in clay soils where structure is essential. Sandy loams, silts and loam soils have intermediate structure between the sands and the clay soils. Organic matter plays a key role in improving the aggregation of sandy soils and friability to heavy clayey soils and promoting a stable structure in medium soils (Davies *et al*., 1993).

1.3.5.2 Soil texture

Soil texture and the proportions of silt and clay together determines soil type which, similarly to soil structure, has significant influence on crop growth. Soil mineral separates of sand silt and clay have different water and nutrient holding capacities and therefore could affect crop growth.

The main difference between sand, silt and clay particles are based on the unchanging characteristics of size and shape which makes the texture one of the basic and constant properties of a soil (Brady and Weil, 2006). Clay particles have much larger surface area and specific surface area (surface area per weight unit) that is much larger than that of sand and silt particles. And since gases, water and nutrients adsorption, as well as, particles attraction to one another are surface phenomena, clay particles play the significant role in water and nutrient holding capacity in the soil. Sand paricles, due to the large size of these particles and the pores that separate them, their water holding capacity is low meanwhile drainage and air movement are high. Silt particles were described as the micro-sand due to their small size and irregular shapes, they don't support air and water movement as much as sand and due to their small specific surface area, they do not have the adsorption properties of clay, unless coated with a film of clay, that gives them some elasticity, attraction and adsorption capacities (Brady and Weil, 2006).

Costigan (1986) demonstrated that soil type affects lettuce growth rate. Lettuce (*cv. Avondefiance*) growth was compared on 13 different soils used in commercial production for four weeks. Small plots of these soil (20 cm in diameter and 20 cm deep from the surface of the soil) were established on a single site. The soil types included Sandy loam, loamy sand, silty clay loam, sandy clay loam and organic). Crop performance in all soils in terms of all the measured parameters; relative growth rate (RGR), tissue concentrations P, K and Mg) was similar, except for N, and they found considerably greater dry weights (two or three times heavier) for the plants produced in what they described as "the best soil" in comparison with "the poorest soil".
Although they found significantly consistent results when they repeated the experiment, demonstrating the effect of soil type on lettuce growth rate, they did not determine the effects of particular differences between these types. They did not clarify what was the best or the worst soil in this experiment or why soils from the same type had sometimes different dry matter results or define the best and worst soil (Figure 1.8).



			Available nutrients (μg/ml)						
Soil no.	County	Texture	P	K	Mg	pH	OM* (%)	CEC† (m-equiv/100 g)	Conductivit (mS/cm)
1	Bedfordshire	Sandy loam	44	240	55	7·5	8·2	28·1	2·20
2	Bedfordshire	Sandy loam	109	416	27	7·3	2·7	12·6	2·23
3	Lancashire	Loamy sand	143	84	37	6·4	3·4	23·4	2·16
4	Lancashire	Sandy loam	26	135	56	6·8	4·8	16·4	2·16
5	Bedfordshire	Sandy loam	92	295	82	6·5	3·5	16·1	2·16
6	Bedfordshire	Sandy clay loam	46	140	71	7·5	5·0	24·4	2·16
7	Hertfordshire	Silty clay loam	32	228	84	7·2	3·7	14·8	2·16
8	Lancashire	Organic	60	188	131	6·3	28·5	73·4	2·19
9	Lancashire	Sandy loam	103	313	34	5·4	4·1	26·2	2·17
10	Lancashire	Organic	129	226	267	7·2	45·7	154·5	2·16
11	Lancashire	Silty clay loam	68	673	251	6·9	8·2	30·6	2·23
12	Warwickshire	Sandy loam	54	179	121	5·4	1·9	13·2	2·17
13	Warwickshire	Sandy loam	88	214	116	5·5	2·9	16·4	2·19

Figure 1.8: The table of soil types used in Costigan, 1986 study, with differences in texture, available nutrients, OM, CEC and conductivity

The correlation analysis between RGR and soil nutrients, pH, Organic matter, cation exchange capacity and conductivity, showed only a significant correlation between RGR and plant content of % P with a major effect accounted for 44 % of the variance of RGR in the first experiment and for 68% of the variance in the second in addition to a positive correlation with the available soil P. However, this difference between the percentage accounted for by the P in the first and the second experiment indicates other important factors that potentially play a key role in yield variation. Interestingly, Costigan (1986) reported a negative effect for the organic matter content on the RGR of the plants when analysed independently from P. This conformed to what they found in two of the high organic matter soils, where plant RGR was much less than what they would have expected from the % P in the plants grown those soils. Therefore, they suggested that the negative effect for OM on RGR could be due to increased CEC where making some of the minor or micro nutrients less available to the plants which could also be due to increased microbial activity, or increased soil temperature to root zone due to enhanced solar radiation absorption because of the darker colour of the soils high in OM (Costigan, 1986). Costigan found no effect for soil pH on lettuce growth rates although some of the soils used in their experiments had pH values of less than 6 whereas the standard MAFF recommendations are a minimum of 6.1 (MAFF, 2000)

A potential limitation for Costigan's study (1986) study is that they applied the recommended fertilizers for each soil (P, K and Mg) except for N they applied uniform amount which they considered to be satisfactory for young plant needs which ignores the effect of N leaching differently from different soils depending on the soil nutrient holding capacity; the negative effect of organic matter that was reported in this study for example could have possibly been due to higher level of N available that cause some toxicity symptoms. Moreover, the size of the plots used for this experiment was likely too small to be a true representation of the source soil types. Twenty centimetres in depth and diameter for each plot is not enough to provide a segregation for the filling soil from the site soil, therefore, the different soil characteristics reported for these plots could still – to some extent- be a reflection of the site soil properties combined with the imported soil.

1.3.5.3 Soil nutrients

Lettuce is fertilised according to recommended obtainable rates depending on soil analysis results for P, K and Mg indexes and also depending on soil nitrogen supply (SNS) index and the rainfall area for nitrogen as recommended by the fertilisers manual (RB20) (AHDB, 2016). This guide has been updated in 2017.

Nitrogen has the most dominant effect on plant growth, mainly through root growth and the production and the transport of the cytochromes (Cyt) from the roots to the shoots which has the key role in photosynthesis and energy transport within the plant, Potassium and Phosphorus are also important for these plant functions (Marschner, 1995).

Lettuce prefers fertile soils with pH level that ranges between 6.5 to 7.2 (Ryder, 1999). Phosphorus (P) is markedly important for early stages of growth, whereas Nitrogen (N) becomes more important with the growth and development of the crop (Ryder, 1999).

Zink and Yamaguchi (1962) carried out 17 field trials in commercial fields in the Salinas Valley, U.S. on seven different soil types. They grew lettuce from seeds from November to August and harvested them continuously from April to October. During this period, they sampled the plants every seven days where they measured fresh weight, dry weight, leaf number, and leaf area and analysed the dry material for mineral content of Nitrate, N, Potassium (K), P, Calcium (Ca), Magnesium (Mg), and Sodium (Na). They found that lettuce absorbs very small amounts of nitrogen during the early stages of growth and that 70 % of the uptake of the nutrients happens throughout the last 21 days before harvest (Figure 1.9) which corresponded to the growth rate of the plant. They recommended that a third of the quantity of nitrogen fertilizers in particular should be added about one month before harvest, to avoid loss of N by early leaching into deep soil water (Zink and Yamaguchi, 1962).

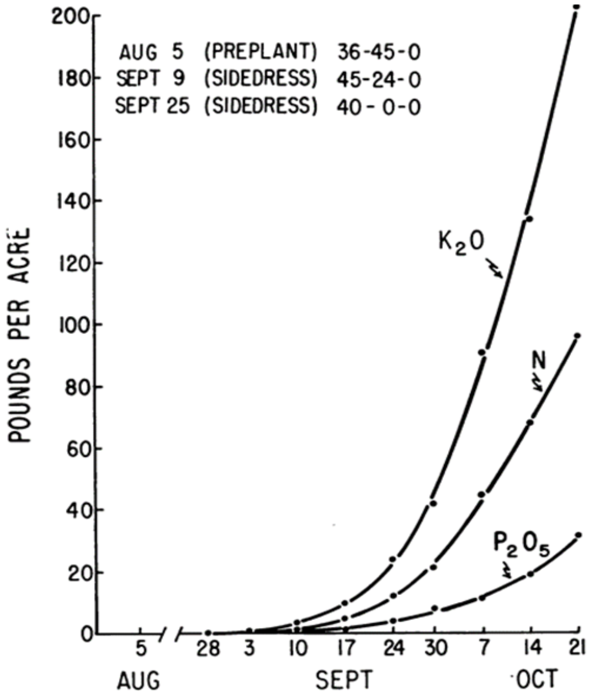


Figure 1.9: Mineral absorption of Potassium, Nitrogen and Phosphorus by the plants during the growth of the trial sawn on 5Th August. Fertilizer rates are expressed as pounds of N, P_2O_5, and K_2O per acre (Zink and Yamaguchi, 1962).

Their work however, did not report adequate soil / field background information and did not include soil testing prior to the experiment.

Costigan *et al*., (1983a) carried out a series of studies examining the relationship between lettuce crop and the effect of nutrients as well as a number of soil factors on the crop growth, quality and development. In some early studies, Costigan *et al*., (1983a) compared the yields of two sites from the same soil series (sandy loam). Historical crop yield data showed a substantial difference between the sites, despite incorporating the maximum levels of fertilizers for each field. They conducted 13 field experiments on seven different vegetables on these two locations. They found that the growth of young seedlings was always restricted on the poorer site and reported differences in fertility and soil physical conditions. Their results showed that despite similarity in pH and water properties, there was a substantial difference in the exchangeable K and P levels, bulk density, as well as organic carbon, which was suggested a difference in soil physical properties between the two sites. The study concluded that the restricted growth in the young plants was due to the poorer site being unable to supply the plants with sufficient potassium and / or phosphorus when plants were small. The fertilizer incorporation did not mitigate this nutrient stress regardless of the added amounts (Costigan *et al*., 1983a). This could be supported by Marschner (1995) when he talked about Potassium depletion zone around the roots of the plants; K and P are normally present in lower concentrations around the root surfaces in comparison with the rest of the soil, creating a depletion zone in the root area (Marschner, 1995). Which meant if the concentrations of these nutrients in the soil are low as well as their availability and if the fertilisers granules were not close enough to the roots and or the depletion zone, then the seedling roots might not be able to extract these nutrients from the soil. Marschner, (1995) also demonstrated the significant effect of soil type and particularly clay content on scale of the depletion zone, mainly due to the effect of clay on the cation exchange capacity, the higher the clay content in the soil the smaller is the depletion zone due to the soil greater ability to replenish the K absorbed by the roots in the root-soil zone (Marschner, 1995).

Costigan work had a number of limitations in that the fields were not adjacent, instead sites were “almost” neighbouring. Although both fields were under different cropping rotations there was no homogeneity test for the two field soils and no information was reported on field topography; Plum Orchard had been a permanent pasture whereas, Big Ground site had been cropped with cereals continuously for many years. Big Ground (the poorer site) had greater bulk density and despite that the seedbed preparation reduced the differences in bulk density markedly for these experiments, the seedbed preparation does not normally tackle the deeper layers of soil, therefor the effect of subsoil or soil structure was dropped from this study. They eliminated the difference in water movement within the soil as a reason for yield variation due to the both sites having very similar water-release curves, water contents and distribution. However, both water-release curves and water content results were based on small topsoil samples (24 cm depth) and do not necessarily represent the difference in water movement in soil profiles (soil structure) for two non-adjacent fields. When Costigan and McBurney’s (1983) followed up this study with further investigation into these two sites, they eliminated the soil penetration resistance as a cause for growth reduction as the values were identical on both sites and were not great enough to hinder root growth.

They followed a complex experimental design for lettuce to examine the effect of five different soil treatments; three N fertilizers levels; 0, 100 and 200 kg. ha^{-1} in addition to two other treatments that relied on excavating the soil down to 25 cm on both sites and replacing the soil with either soil from a third field, so that lettuce grew in the same soil but on different sites, once with the original third-site soil and once with adding a medium level of N fertilizers with 120 kg. ha^{-1} to the third soil. There was no difference in plant contents of N between the two sites. Yields from all experiments were always greater on Plum Orchard than on Big Ground. Excavating the native soil and replacing it with soil from a third field resulted in 30% yield reduction on both sites. Despite the time to emergence and the emergence rate being similar in both sites, the dry weight of plants was significantly higher in Plum Orchard than on Big Ground. Harvested plants from Big Ground had less content of potassium and phosphorus than Plum Orchard. They concluded from their results that a lack of potassium and phosphorus was the key reason behind the observed yield difference, where better growth at early stages on Plum Orchard created weight difference that persisted through to harvest, as the difference in dry matter was always established early in the crop cycle. Incorporating fertilizers into Big Ground, regardless of the added quantity, was not sufficient to improve the soil ability to supply potassium and phosphorus to the plants to increase the yield. However, they were unable to confirm this conclusion when they compared soil potassium levels from both sites to tables of critical values for each crop (Chapman, 1966) and found no indication of lack of potassium in either site.

Further glasshouse studies into the difference in yield of lettuce grown on these two soils used soil from the top 15 cm of both fields and supplied it with three levels of N fertilizers (0,100 and 200 kg. ha^{-1}), three levels of phosphorus as triple superphosphate (P_2O_5) (0, 87, and 174 kg ha^{-1}) and three levels of potassium as potassium sulphate (K_2O) (0, 87 and 374 kg ha^{-1}) (Costigan and McBurney, 1983). Measurements showed that the highest concentration of N fertilizers (200 kg ha^{-}1) reduced the yield and explained this reduction as a lettuce response to salinity or ammonium toxicity. Which conforms to the results of a more recent study by M’hamdi *et al*., (2014) as they examined the effect of another two close doses of N fertilisers (120 and 240 kg ha $^{-1}$) on six lettuce cultivars and found that the highest yield was achieved at (120 kg ha^{-1}) exceeding this level to 240 kg. ha-1 resulted in reduced fresh weight for five of the cultivars also except *Vitalia* and reduced the head diameter for all six cultivars and in raising the nitrate accumulation in the plants beyond the standard limit is 2500 mg Kg -1. However, M’hamdi *et al*., (2014) did not state the soil type and their experiments were done in a hotter environment (Tunisia) which complicates the comparison between the two research.

The effect of native soil potassium and phosphorus was studied in a subsequent field experiment where optimum recommended fertilizer rates were broadcast into the seedbed of both fields. The fertilisers added were N (as ammonium nitrate), phosphorus (as ground triple superphosphate) and potassium (as potassium sulphate). The rates that were used were 78, 300 and 150 kg ha $^{-1}$ of N, P_2O_5 and K_2O respectively. Additionally, a top dressing of 92 kg ha^{-1} N was added 28 days after planting. The crop was sampled 10 times at regular intervals from 7 to 73 days after germination (including the roots for the first three harvests) (Costigan and McBurney, 1983). Seven and nine days-old plant tissues on Plum Orchard (PO) contained 86 % and 107 % more K than those grown on Big Ground. They also recorded reduced growth in the lateral roots on the poorer site, as well as reduced relative growth rate up to 40 days from sowing. They concluded that the limited growth on the poorer site was due to lack of native soil potassium and possibly phosphate that the fertilizer granules were not capable to compensate for the seedlings. In addition, it was suggested that large difference in potassium levels at early stages of growth to be responsible for changing growth and development patterns and reducing root / shoot ration, making the plants more susceptible for phosphorus deficiency and water stress, as lack of K can result in reduced growth of lateral roots as relatively large amounts of this element are needed for maintaining the turgid state of the meristematic cells and allowing cell expansions and divisions. This, in fact, can be supported by Zink and Yamaguchi (1962) study where they found that maximum uptake of nutrient and growth in lettuce occur during the last three weeks before harvest as shown in Figure 1.9. Costigan and McBurney's (1983) suggested that the low nutrient concentrations in the plants grown on this site to be indicative of nutrient deficiency despite broadcasting the optimum amount of recommended fertilizers for this field. And although they referred to the possible effect of the spatial variation in native K distribution in BG. They considered that native potassium distribution was naturally homogenous and was too low to supply the plants. And so, the broadcasted fertilizers were widely spaced that could not supply all seedlings evenly. Therefore, their study could have benefited from geo-refencing the sampling locations to support their conclusions. However, they did not include any assessment of the homogeneity/variability of the in-field soil or nutrient levels. Meanwhile, the native nutrient concentrations on Plum Orchard were adequate to supply the small seedlings. Another limitation to this study was that the soil was kept permanently wet throughout the whole crop cycle which might have masked the effect of some variation in soil water / hydraulic properties between the two sites. Prominently, they highlighted the fact that after emergence, the initial factor causing growth difference might be difficult to distinguish solely from studying growth rate and nutrient contents alone. And once this difference in growth was initiated and the concerned factor had affected the plant roots in particular, all other growth parameters will be disturbed. Therefore, they emphasised on the importance of sequential sampling that covers the period from before till after the occurrence of the growth difference. And the sampling after germination and before emergence as an indication of soil fertility. The difference in K persisted later in the season whilst a difference in P has developed later on. Moreover, having both field been under two different cropping systems and possibly different cropping or land use history, requires more information about the difference in organic matter levels or the potential presence of any negative toxic or pathogenic factors in the poorer site.

Costigan, (1984) concluded that soil with large residue of nutrients results in better crop growth than soils containing little or no nutrient residues despite broadcasting the appropriate amount of fertilizers for each soil and they attributed that to the fact that small plants/ seedlings at early stages have very small roots that exploit only small space of the surrounding soil and therefore they might not encounter any fertilizer granules which expose these plants to nutrient deprivation in poor soils. Therefore, it was suggested that adding the starter fertilizers immediately 1 cm underneath the seeds, particularly phosphate to satisfy the demands of the small plants in the first few weeks of growth.

Lettuce cultivars appear to vary in terms of N use and nitrate accumulation, as observed by M'hamdi *et al*., (2014) study, which found that the moderate N treatment (120 kg ha^{-1}) gave the highest fresh weight values for all of the studied cultivars except *Vitalia*, and the highest N fertilizer level (240 kg ha^{-1}) reduced fresh weight for all the cultivars also except *Vitalia*. M'hamdi's study highlighted the importance of N fertilizer level in determining the nitrate accumulation in lettuce leaves and that when the N fertilizers level increase, the nitrates accumulation in the plant tissue increases too. This was also reported by Hoque *et al*., (2008) who found that the accumulation of NO_2^- and NO_3^- in the plants is influenced by several factors including the type of the N fertilizers, the amounts and the time of application.

Selecting the appropriate sources and doses of N fertilizers has significant impact on reducing the occurrence of N toxicity symptoms and related yield losses. Hoque *et al*., 2008 found that high concentrations of nitrite (NO_2^-) and nitrate (NO_3^-) in leafy vegetables as a result of excessive uptake of N by the plants can lead to serious effects on human health. Therefore, precision in identifying the time and the amounts of nitrogen fertilizers is a key into minimizing the vegetable contents of NO_2^- and NO_3^- whilst optimizing the yield.

Another reason that necessitate precision in nutrients management in general and nitrogen in particular is to protect the crop from toxicity. Marschner, (1995) divided plant response to nutrients into three stages; the growth increases in response to nutrients increase in the first stage, the growth then stops increasing in the second stage where nutrients reach an adequate level and their increase no longer leads to increase in dry matter, and in the third stage / region, the increase in nutrient supply leads to reduced growth as a result of toxicity (Figure 1.10) (Marschner, 1995).

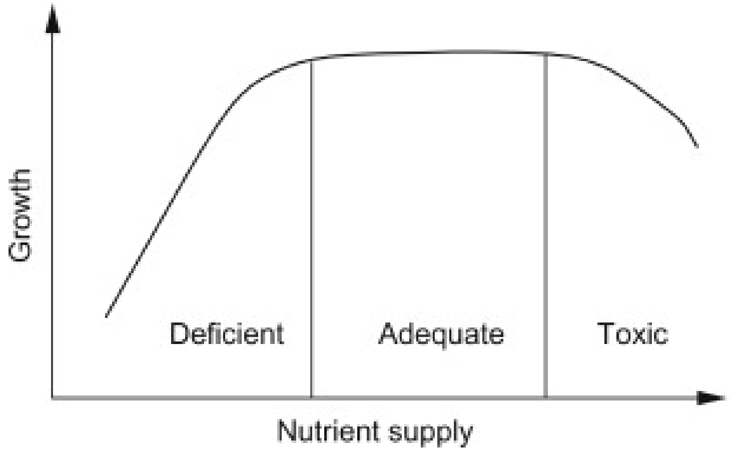


Figure 1.10: Nutrient supply versus growth curve (Marschner, 1995)

Hoque *et al,* (2008) carried out two glasshouse experiments in hydroponics, where they compared in the between N toxicity symptoms caused by each of NH_4+, NO_2^- and NO_3^-. And examine the toxic or repressive effects of six concentrations of NO_2^- on lettuce. They found that both NH_4^+ and NO_2^- suppressed lettuce growth more significantly than NO_3^-. They reported N toxicity symptoms to be stunted growth, delayed maturity, necrotic spots, hollow roots that could eventually exude discoloration and rot. Young leaves can become darker in their green colour whilst older leaves become yellow (Hoque *et al.,* 2008). Hoque also noted that Ammonium (NH_4^+) toxicity in particular is more common in Iceberg lettuce than in Romaine lettuce (Hoque *et al*., 2008). Furthermore, a field study done by ADAS in 2014 on N repose in baby leaf lettuce found that mostly, with low SNS such as index zero where the recommended amount at drilling is 30 - 60 kg N/ha at 0- 30 cm the crop is most likely to need a maximum of 60 kg / ha and that in some cases, this amount is enough to raise the tissue nitrate content in the leaves above the regulations' limits.

1.3.5.4 Effect of irrigation and soil moisture content

In recent years, there has been an increase in water management studies for crops, due to the increasingly limited water availability in leafy salad production areas including lettuce (Luna *et al*., 2012). The physiological importance of water supply comes primarily from its direct effect on transpiration and gas exchange rates in the leaves that allow normal photosynthetic function. Because adequate water supply means stomata can remain open, which in turn control the plant dry matter production functions (Kerbiriou *et al*., 2013a and Taiz and Zeiger, 2010).

In lettuce, water application, (along with nitrogen fertilisers) is very important for maintaining optimal growth and development. This is primarily because the harvested part of this crop is the photosynthetic part (leaf area), so regular water applications are commonly provided at early stages of growth for young lettuce plants to ensure good yield provision (Gallardo *et al.,* 1996). The number of water applications that lettuce crops need varies depending on temperature, soil texture and the length of the crop cycle (Ryder, 1999).

Gallardo *et al.* (1996) investigated the effects of a range of water regimes on the production and water use of three lettuce cultivars. The regimes simulated different field irrigation scenarios and were obtained by watering the plants to field capacity and 13 %, 30 % and 55 % below field capacity. They found a large loss of water by evapotranspiration to occur during mid-season where lettuce in particular is not sensitive to increased irrigation at this stage. They identified this period to be the time just after thinning (around 24 days after planting). Therefore, they suggested reducing irrigation during this period. They also found that the period in which lettuce was particularly sensitive to the irrigation treatments was the period to be between 54 and 63 days after planting. Therefore, they suggested that the most important amount of water given to the crop is that provided in the last three weeks.

In addition to insufficient water supply, excess irrigation can also negatively impact lettuce production. Luna *et al*. (2012) examined the effects of five drip irrigation regimes (irrigating 25% and 50 % above the control (conventional irrigation) treatment, and 25 % and 50 % below the control) on lettuce quality and shelf-life. The irrigation regimes used combined water supply, rainfall and Evapotranspiration balance.

The highest water regime corresponded with the lowest fresh weight, dry matter and a higher maturity stage. In addition, the visual quality and shelf life was compromised whilst the off-odours increased.

Variability in soil type has a significant effect on lettuce establishment at early stages of growth as demonstrated in Costigan's (1986) study. Also due to the variable capacity of deferent soil separates to hold water (Brady and Weil, 2006) therefore variable textures across the field with variable contents of sand, silt, clay and organic matter will result in variablilty in the available water content.

Young lettuce plants are very sensitive to drought due to their shallow root systems (Gallardo *et al*., 1996; Kerbiriou *et al*., 2013a and Jackson, 1995). Exposing lettuce to drought during early stages of growth can slow down shoot and root growth (Kerbiriou *et al*., 2013a and Johnson *et al*., 2000).

At early stages of lettuce growth, both biomass production and leaf development are slow which delays the soil coverage by the crop, resulting in greater water loss by evaporation from the soil surface (Gallardo *et al.,* 1996). Decreasing water supply can reduce the evaporation contribution to the total evapotranspiration of the crop (Gallardo *et al.*, 1996).

However, decreasing the water supply too much can lead to water stress conditions which have adverse impacts on the plants. For example, lack of contact between the soil water solution and root surfaces due to low soil moisture content can impair the uptake of nutrients such as potassium and phosphorus (Marschner, 1995) which can explain further Costigan's (1986) study findings that early difference in growth between the two sites that he studied was associated with lack of potassium and phosphorus due to soil differences. Under water stress conditions, the growth of the fine root hairs sometimes enhances under water stress and become particularly important as this can partially compensate for the reduced water uptake elsewhere in the root system (Marschner, 1995). Indeed, root growth and density play a key role in determining lettuce response to water supply. Kerbiriou *et al.,* 2013a examined the responses of two lettuce cultivars to both temporary and continuous drought in terms of root and shoot growth. The study found that lettuce roots undergo changes to preserve resource access in water-limiting environments. The study also concluded that lettuce roots might respond to transient water stress through functional or morphological changes that can support the plant growth in an environment of limited resources, where root growth, exploration and expansion were increased by drought compared to well-watered plants.

1.4 Understanding the interaction between soil type and soil physical quality and its effect on crop production

Soil quality is categorised into three aspects; biological, chemical and physical although these three aspects are strongly interrelated. Soil physical quality has a significant effect on its biological and chemical status and so measuring the physical quality of the soil is a major part of assessing its overall quality (Dexter, 2004a). Soil bulk density, organic matter and clay content are some of the most frequently studied physical soil properties with regards to their effect on soil quality and crop yield (Dexter, 2004a; Loveland and Webb, 2003; Arvidsson 1998; De Benedetto *et al*., 2000 and Qiu *et al*., 2016). This may be due to their multidimensional effect on other soil properties. Together, all three of these properties partially form the soil texture. Clay content in the soil for example, plays a role in its stability under irrigation and land preparation, as clay particles carry calcium ions on their surface which protect the soil from dispersing in water to some extent and keep them flocculated. In dry regions, the calcium ions can be replaced by sodium ions on the clay surface, resulting in the sodicity problem which is associated with poor physical properties of the soil such as permeability, degradation, excessive shrinkage and swelling and thus no-workability status (Dexter, 2004a). Marschner (1995) also described the critical role that soil texture and structure plays in determining the availability of nutrients for plant uptake; soils with greater bulk density provide greater contact between the roots and the soil.

Quantifying soil physical quality has been attempted through a number of theoretical studies by Dexter (2004a). The author considered the value of soil physical quality to be the extent to which pore sizes in the soil are concentrated into a narrow range which indicates a better-defined microstructure for the soil and gave it the symbol S. S is equivalent to the slope of the water retention curve of the soil at its inflection point when it is plotted as logarithm of the water potential against the soil gravimetric water content.S was found it to be a better predictor of soil rootability than the bulk density of that soil. Dexter (2004a) considered S to be the determinant factor of a soil's physical properties and its function in agriculture production. Whilst Loveland and Webb (2003)'s review of critical ranges of soil organic matter content (OM) concluded that there is no definite value below which soil structure breaks down, Dexter (2004a) found 4.2 % and 1.2 % OM to be the critical levels for silt loam and loamy sand soils, below which poor physical quality of the soil started to occur. When bulk density and organic matter were used in calculating S organic matter had greater effect on the S value in soils with low clay contents than in soils with higher values of clay (Dexter 2004a).

A good soil quality is commonly associated in the literature with organic matter content due to benefits such as better rooting intensity for the crop, reduced compressibility or machinery effect (Loveland and Webb, 2003). Nevertheless, texture and bulk density is as equally important in soil stability and workability (Brady and Weil, 2006). Variability in soil texture is a key influencing factor that affects the in-field variability in organic matter (Qiu *et al*., 2016).

When soil is compacted (has high bulk density), the larger pores tend to be lost first by being reduced in size, which changes the soil water holding and retention properties, unless the soil reaches an equilibrium via a strong structure where it starts to endure the applied stress without further loss in pores (Dexter 2004a). However, the use of soil bulk density to compare the physical quality of soils with changing or different densities could be problematic due to the variability of soil volume or quantity in the dominator, similarly the use of volumetric water content will not be meaningful (Dexter, 2004a). In agreement, Lark *et al*., (2014) considered bulk density to be one of the most difficult soil properties to measure and assess due to the extreme precision needed while extracting the exact core volume of soil and the core extraction itself will cause disturbance for the sample which will affect its density. Dexter (2004b) followed up by demonstrating further that soil friability and workability was strongly correlated with soil physical quality and that soil physical quality could be a better predictor of soil friability than direct measure of soil friability itself due to easier means of assessments and so less error in recording.

Organic matter levels are significant factors in reducing the soil bulk density and the damaging effects of compaction by farm traffic (Arvidsson, 1998). Soils with more than 50 g. kg $^{-1}$ organic matter under traffic had greater yields, air content and porosity in comparison with un-trafficked soils However, for soils with less than 30 g. kg $^{-1}$ organic matter, farm traffic reduced yield by 11%. These results did not match with laboratory findings however, with the compression index being positively correlated with clay content, but organic matter content was not associated with a decrease in compactness or increase in air content. Very little effect of soil particle size on the compression index was found. It is possibly that the number of compressed samples that Arvidsson used per each site (2 per site) was too small to represent the compressibility of the field soils, especially considering that the amount compressed in the uniaxial compressor was very small (80 g) stretched inside 72 mm diameter cylinder, therefore, a higher number of replicates could have given more comparable results. Moreover, although the soil was rewetted to field moisture level at the time of sampling, the soil samples used where still considerably disturbed (dried, sieved, etc.). Arvidsson (1998) stated that organic matter had more effect on the yield and the physical quality of the soil than soil particle size distribution. They suggested that the increase in crop yield under traffic in soils with higher organic matter suggest that organic matter can increase the loosened soil need for compression to improve the yield. This could be explained by maximizing root contact with the soil.

1.5 Understanding soil variability

Soil factors that influence crop production interact with climatic conditions and agricultural practices creating a complex source of variability in field crops. Understanding the spatial variation of soil factors is fundamental when assessing spatial patterns of yield and for making informed precision farming decisions. Soil is heterogeneous with respect to nutrient availability due to the dissimilarity of the breakdown activity (St. Johne *et al*., 1983). A considerable amount of literature investigated the vertical and horizontal spatial variability of soil nutrients and fertility as influenced by external factors (Rivero *et al*., 2007; Mzuku *et al*., 2005 and Cambardella *et al*., 1994). Some studies considered the ecological aspect of soil spatial variability, attempting to measure the geographical distribution of soil fertility as influenced by environmental conditions (Jobbagy and Jackson, 2001; Gutierrez *et al*., 1993) others viewed it from an agricultural perspective, with reference to the effect of agricultural practices (Duiker and Beegle, 2006). More recent studies attempted quantifying soil heterogeneity and examining how this variability influences crop production targeting mostly cereal and long season crops (James *et al*., 2003; Taylor *et al*., 2003, Earl *et al*., 2003; King *et al* 2005; Stadler *et al*., 2015; Landrum *et al.,* 2015).

For soil nutrient distribution in the top 100 cm using global soil data, it is difficult to explain vertical patterns in nutrient distribution without considering the influence of plants on the upward transference of nutrients (Jobbagy and Jackson, 2001). Cambardella *et al*. (1994) investigated the spatial variability of 28 different soil factors in the U.S and found that 12 of them displayed a natural distribution and the remaining 16 parameters, including; organic carbon, total nitrogen, pH and macro-aggregates were variably distributed. The authors emphasised the role of scale in strengthening the measured spatial relationships and that in order to examine the variability of a soil factor, the study scale needs to be appropriate for the research question. Horizontal variability in the spatial distribution of nutrients can also be influenced by the dynamics and the mobility of these nutrients, especially nitrogen. Marschner (1995) predicted the nitrate supply from the top soil to the root zone to be different from that of phosphorus and potassium due to the capacity of nitrate to be transported by mass-flow, contributing to the supply to the root surface.

Furthermore, the temporal variability in crop production adds to the complexity of interpreting the spatial variation in yield that is resulting from spatial variability in soil factors. Costigan and McBurney, (1983) suggested that variation could occur from crop to crop due to the variability in physiological status and requirements as well as other characteristics such as seed size, planting method, the growth period of each crop, which result in difference between crops in the ability to extract water and nutrients.

Generally speaking, and considering the literature reviewed for the purpose of this study, the main soil factors that affect crops and other plants variation are; moisture and nutrient holding capacity, soil friableness and workability, soil structure and drainage as well as soil health. The frequency of these factors and what each one entails of subfactors as appeared in literature allows considering this list to be in the order of importance from the most to the least important.

1.6 Quantifying soil variability:

Field to field soil variation is common in the UK (Costigan *et al*., 1983a). Soil variation poses challenges for soil scientists as to how to sample, analyse or study soil properties. Precision crop management concepts have emerged as a result of the effect of soil variability on plant growth and crop yields. Variable field soil (chemically or physically) can affect nutrition and water supply for the crop across the field. Uniform application of water and fertilizers to a field soil of variable properties could result in excessive or insufficient water provision and nutrient availability in some parts of the field.

Marschner, (1995) noted that conventional soil analysis (sampling and testing) for determining the nutrient availability is limited due to its dependence on homogenised and processed soil samples which lose information regarding the spatial variability of soil nutrient availability and destroy soil structure. Precision farming has been promoted by the expansion of technologies such as remote sensing, mapping and data-management software and the Global Navigation Satellite System (GNSS) (Godwin and Miller, 2003; Corwin and Lesch, 2005; Doolittle and Brevik, 2014). These technologies support noninvasive soil sampling and assessments whilst providing the capacity to obtain a greater volume of data more rapidly than conventional soil assessments. One of the most important technologies adopted in farming is that of soil and yield mapping. in commercial settings, when grids are used, mapping is commonly conducted using a 100 m x 100 m grid and although rarely used in commercial farming, carefully targeted profile pits provide valuable information about the field and soil function (Earl *et al.,* 2003). Another commonly used method for sampling for soil pH and nutrient assessments is that of bulking samples collected from the field through walking a W shape from one end of the field to the other done (MAFF, 2000 and Earl *et al*., 2003). A recent case study by ADAS that was published in The AHDB Grower magazine also examined three different sampling approaches for demarcating variable pH and P zones across a field in Bedfordshire, UK. They used three sampling densities, conventional (the W shape composite sampling method consisting of 25 subsamples), grid sampling (1 composite sample per ha consisting of 16 subsamples) and grid sampling (2 composite sampling per ha each consisting of 16 subsample). In the grid sampling, the subsamples were collected in a spiral pattern within a 3 m radius from a central point. The case study found that although the less intensive grid and the conventional sampling method provided a good estimate of the mean values, the more intensive grid sampling revealed field variations that were overlooked in the first two methods.

Until recently, farmers have treated arable land uniformly (Stafford *et al*., 1996; Corwin and Lesch, 2005) without considering the natural variation in soil conditions within or between fields. With the introduction of yield mapping and precision agriculture, vital benefits of soil apparent electrical conductivity (ECa) scanning emerged for soil mapping such as identifying management zones, determining variable seeding rates and targeted soil sampling (Grisso *et al*., 2009). Soil ECa scans have been recently implemented in a broad range of studies to describe or define spatial variability in soil properties (Doolittle and Brevik, 2014; Zhu *et al.*, 2010; Corwin and Lesch, 2005; King *et al*., 2005).

1.6.1 Soil apparent electrical conductivity (ECa) and mapping

A material's capacity to transmit electrical current is termed electrical conductivity (EC) and is reported in units of milliSiemens per meter (mS/m) or in deciSiemens per metre (dS/m) (Grisso *et al*., 2009). Soil electrical conductivity is simulated by a mix of physical and chemical factors so it is termed "apparent" (ECa) (Corwin and Lesch, 2005). Soil ECa scans and the electrical properties of the soil are defined by a complex interaction between soil contents of clay, organic matter, water, as well as soluble salts (Earl *et al.,* 2003). Factors that can affect crop yields and could be estimated indirectly using ECa have been reported to be; soil temperature, clay, salts, minerals, water content, organic matter, bulk density, water holding-capacity, pH, minerals, topsoil depth, water-table depth, compaction and water flow patterns. (Corwin and Lesch, 2005; Ma *et al*., 2011; Grisso *et al*., 2009; Zhu *et al.*, 2010; Doolittle and Brevik, 2014). Soil ECa is predominantly measured commercially, for agricultural or scientific purposes, by two types of soil sensors; contact-based sensors (e.g. Veris technology sensors; requires direct contact with the soil, Figure 1.11) and non-contact-based sensors (e.g. DUALEM or Genomics sensors, Figure 1.12) (Serrano *et al*., 2014)

Figure1.11. Contact-based sensor (Veris) (Source: Veris Technologies, 2014)

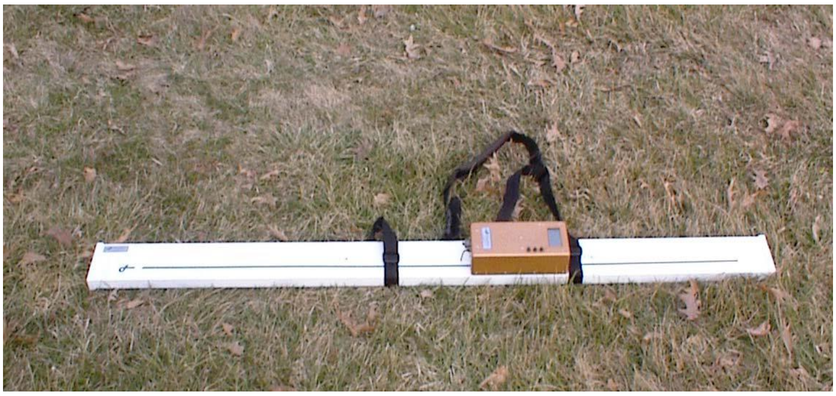


Figure 1.12. non-contact-based sensor (Source: Ohio State University, 2015)

The contact-sensor is based on voltage drop; measuring soil electric-resistivity (impedance) of current flow between transmitter and receiver coils. The non-contact-sensor is based on the principal of electromagnetic induction (Faraday's Law), where an electric current is introduced to the soil that induces an electromagnetic field. This field produces eddy-current loops (secondary electric field) that also depend on the conductivity of the soil (Serrano *et al*., 2014). Walter *et al*., (2015) distinguished between two parts of the soil electric conductivity; the real part which is mainly associated with the pore-fluid conductivity of the soil and cation exchange capacity (CEC), and the imaginary part which is associated only with CEC (Walter *et al*., 2015). The importance of ECa in soil assessments comes mainly from the fact that different soil types have different EC (e.g. clay soils were commonly noted to have higher ECa ranges than sandy soils).

Hence, the variability in soil ECa is created by the dissimilarity in EC of the substrate's different materials (Doolittle and Brevik, 2014). The electric properties of peaty and organic soils are also different from those of mineral soils and there is little published literature about them and there has been little implementation for the electric conductivity surveys on peatlands (Walter *et al*., 2015). By the difference in surface properties, in organic and peaty soils (differently to mineral soil) surface-related properties (such as CEC) make a major contribution to the electric properties of the soil which is the main difference between organic and mineral soils (Walter *et al*., 2015).

1.6.1.1 The use of soil scans and yield maps in precision agriculture (PA)

Two approaches for precision agriculture mapping of in-field variability have been described; identifying low-yielding zones within the field (yield approach, Keller *et al*., 2012) and demarcating in-field homogenous zones (soil approach, Landrum *et al*., 2015). Parallel studies in precision irrigation have focused on the distribution of water requirements across the field, (Keller *et al*., 2012; Misra and Padhi, 2014 and Daccache *et al*., 2015). In general, ECa maps have been used for identifying in-field distinctive zones. Earl *et al.* (2003) evaluated five different methods of quantifying variability in soil nutrients, soil type and physical properties for practical farming decisions. The authors compared maps produced from hand-auger sampling, targeted soil profile pits, mechanised soil mini-coring and maps generated using measured ECa and mechanised coring of soil. It was found that for identifying soil type in specific zones, conventional sampling techniques were suitable. However, the practical limitations of this approach were the time and cost requried, which limited the sampling density and in turn resulted in the collected data being insufficient to demarcate boundaries of soil-type zones. Mechanised soil coring overcame the cost and effort limitations but time continued to be a limiting factor. Therefore, it was concluded that EMI scans reflect the general variation of soil type were recommended as an efficient alternative to conventional soil sampling, which conforms to the recommendations made by Grisso *et al*., 2009; Zhu *et al*., 2010 and Doolittle and Brevik, 2014. When comparing between two densities of soil sampling (1 and 4 - 8 samples / ha) in relation to ECa maps created using EMI scans, James *et al.* (2003) found the correlation between ECa map and the intensive soil survey (8 samples / ha) stronger. Therefore, it is understandable that the scale of the variation, the individual soil property under study as well as the type of the studied soil have an impact on the sampling methodology and mostly impose added challenges on soil scientists. Lark *et al*., (2014) demonstrated that the sampling density and the sampling protocol that gives the least Root Mean Square Error (RMSE) are zone-specific for bulk density and vary with depth from soil surface and with soil type (mineral to peaty soil) and gave a minimum number of samples required for each soil depending on the scale of variation. However, the validity of this sampling recommendations is worth rethinking, considering the complex effect for the degree of decomposition on the peat properties, which in turn differ vertically in the soil profile (Walter *et al*., 2015) these factors was not considered or discussed in Lark's study.

Although the number and the location of the targeted profile pits that Earl *et al*., (2003) used was justifiable based on crop yield observations, the initial grid that they relied on to study soil variation and determine the targeted location for the profile pit excavation, have possibly not been dense enough. A more intensive grid would have been more informative. Another limitation for this survey is that it had been done in 1987 which meant a minimum of 10 years period between the survey and the excavation of the targeted profile pits. Moreover, not all methods were replicated on all of the five fields, for example mechanised soil coring was done on one field only which doesn't allow comparison of the results with another fields. Taylor *et al.* (2003) compared cereal yield maps to soil ECa scans generated from an EMI scanner and a detailed soil survey conducted using mechanised soil coring to evaluate soil conductivity as a substitute for conventional sampling. Taylor *et al.* (2003) used a more intensive grid (25 m X 25 m) than Earl *et al.,* (2003) for conducting the soil survey. And whilst Earl *et al.,* (2003) did not look at yield responses, Taylor *et al.* (2003) examined the spatial distribution of the yields and their correspondence to soil series and soil data under uniform inputs. It was found the different soil zones that were identified by the soil scans or by different soil series to coincide with yield variation patterns and found that yield variability was more significant in drier years, where differences in soil moisture and dynamics were clearer as to be caused by soil-texture dissimilarity (Taylor *et al*., 2003). Also, in drier years, soil ECa maps corresponded better with yield maps. This agrees with the findings of both Earl *et al.* (2003) and Stadler *et al.,* (2015). Earl *et al.* (2003) recommended to scan the soil in drier seasons. Soil moisture level is known to be important when scanning for ECa due to the relationship between soil moisture-content and soil type or texture which is expressed as water retention properties; the higher the soil moisture content in the soil the less is the difference in moisture across the field and hence ECa values would be less reliant on (less correlated with) moisture differences and more reliant on other soil properties (Costa *et al*., 2014). Therefore, the commercial recommendations are to scan ECa at field capacity as was also done by James *et al*., (2003), However, most of the reviewed studies did not specify any soil conditions under which scans are preferred to be done (King *et al.,* 2005; Misra and Badhi, 2014; Doolittle and Brevik, 2014; Zhu *et al.*, 2010). Stafford *et al.* (1999) also examined yield data for 60 fields of combinable crops in England and found significant yield variation within the same season with inconsistency in yield patterns of the same field. The study attempted to identify field-units that displayed a limited number of distinctive seasonal patterns, hypothesising that these units will correspond to key factors that determine the yield. Frequent spatial patterns within the yield were identified, and these patterns were relevant in most cases to farmer's knowledge of where the low and the high yielding zones of the field were. However, they did could not underpin the soil factors that controlled these patterns, this could possibly due possibly because nutrient and pH and texture for this experiment were obtain from historic soil data, and they only used the mean value for each parameter for each yield data class. The only soil data set collected at the time of the experiment was for gravimetric water content and this was based on 100 m to 200 m grid which is relatively widely spaced grid. Blackmore *et al.* (2003) differentiated between two terms for yield variation; the inter-year variation (the difference in the overall yield from year to year), and the temporal variability (when a particular zone of the field yields differently from year to another). It could be understood from these terms that inter-year offset is a result of the total temporal variability.

Stafford *et al*., (1996) mapped the yield in cereal crops, using a yield mapping system of mass flow sensing for the grains of cereal crops with in-field Global Positioning System (GPS) of accuracy 2 - 3 m. Maps were compared for four successive growing seasons. Soil samples were taken at 1 m depth at 20 m intervals along the 100 m Ordnance Survey co-ordinate lines and soil available nitrogen, phosphorus, potassium and particle size distribution measured. No significance dependence between the yield and the soil nutrients was found. However, yield patterns (despite low consistency from one season to the next) coincided with soil series therefore it was suggested that this would be related to the soil water availability.

Overall, there seems to be an inconsistent correlation between soil electric conductivity and crop yields, and this was confirmed by a number of studies, due to the soil properties that influence soil ECa being sometimes critical for determining crop yield but not all the time (Corwin *et al*., 2003 and Corwin and Lesch, 2003). The key soil properties that determine the yield varies from one crop to the other. Therefore, in cases where crop yields correlate with the same soil factors that correlates with soil ECa, the ECa scans can be very beneficial in predicting yield variation, for example in cotton (Corwin *et al*., 2003). This study identified several reasons for yield abnormalities across the field: some zones were characterized as highly leached locations, other zones had reduced yield due to increased salinity, increased soil available water or high pH. In all of these areas, the recommended solutions had one thing in common which was manipulating water applications in terms of timing and distribution. For example, they found that in areas with higher clay content, the higher soil available water can be reduced by reducing irrigation frequency whereas this frequency should be increased in more sandy-textured area. This is in agreement with the views of Stafford *et al.,* (1996), who suggested the relationship between cereal yield patterns and soil series expressed by soil texture. Corwin et al., (2003) also recommended, for further delineation of the suggested site-specific units, overlaying the spatial information layers using GIS applications (Geographic Information System).

Corwin *et al*., (2003) concluded that exclusive use of either crop yield maps or ECa maps to explain yield variability or informing precision farming decisions is invalid, as yield maps although potentially providing the best indication of soil edaphic factors or external factors such as biological, anthropogenic or weather factors, are insufficient on their own to underpin the interactions of all these factors. They are not always obtainable and are not developed (in terms of equipment) for all crops. Similarly, ECa scans, do not include information about yield responses and variation. Each is a “piece of the puzzle” for understanding the “cause-and-the-effect factors” underlying yield variability. This was supported by the findings of King *et al*., (2005) who conducted a similar study and reported that both yield and ECa scans hold valuable information that relates to the spatial distribution of soil properties but there was no consistency in either of the two maps being a stable representative of soil spatial variability across the whole field (King *et al*., 2005). All or most of the studies cited in the previous section were based in arable fields and examined the spatial and temporal variability amongst arable and long season crops. These studies acknowledged the differences in variability patterns and causes amongst these crops. Therefore, transferring these outputs to horticulture or short season crops is challenging. The studies frequently highlighted that temporal variability in these crops was greater than spatial variability (Blackmoore *et al*., 2003; Casa and Castrignano, 2008 and Stadler *et al*., 2015). It was clear from reviewing literature on quantifying crop and soil variations that advanced tools that handle such data are of great importance. Geographic information system tools and softwares such ArcGIS enabled visualising and analysing spatial data through location recording and map creating as well as performing an extensive range of mathematical analysis such as interpolation. Interpolation is particularly important when estimating unknown values between disconnectedly collected data points.

Panagopoulos *et al.* (2006) compared three methods of spatial interpolation in GIS; Thiessen polygon, inverse distance weighing and ordinary kriging, whilst attempting to optimise the lettuce crop management in a salinized field. Panagopoulos found that kriging was the best technique for mapping each soil property. The resulting maps were overlaid in GIS and the data reclassified to build an optimal map for lettuce production, described as a “lettuce production capability map” to determine which areas in the experimental plot had the optimal conditions for lettuce growth. No optimal zones for lettuce production were found; however, some problems in soil properties that could be resolved via site specific amendments could be localised. There was, however, a strong correlation between actual lettuce yield and the predicted yield obtained from the capability map.

Panagopoulos *et al.* (2006) highlighted the weaknesses of random and convention soil sampling methods while attempting to underpin the spatial relationships of soil factors and crop growth. that the authors consider geostatistics can be the most appropriate inexpensive tool to put precision farming into practice. This was supported by the findings of Qiu *et al*. (2016) who also compared classical and geostatistical analysis methods for the determination of the spatial variation in organic matter, available nutrients and texture. Using semi variograms (a graphical method of measuring the spatial dependence between two variables in relation to the distance between them) and kriging (a method of interpolating spatial data) maps showed moderate autocorrelation for the measured soil properties and found a correlation between the spatial variability in organic matter and soil texture. Kriging maps allowed identifying that spatial pattern of the nutrients. It is considered that the in-field sampling strategy for soil should take into consideration the precision level required for the estimated soil property

In addition to the variation controlled by edaphic factors (soil-generated or soil-controlled factors) there is the additional variation caused by farming practices and transplants handling. This non-field-related variation was acknowledged in some studies (Wurr *et al*., 1987 and Wurr and Fellows 1983), which noted the variability in seed emergence as well as the variability in transplant sizes between batches due to variable glasshouse conditions. Harwood *et al*. (2010) modelled Iceberg lettuce yield based on weather variables and found variation in transplant sizes to be a major contributor to the final yield variation. The authors considered systematic variation in lettuce yield across the field to be result of edaphic and microclimatic factors. The authors superimposed in-field variability on inherent plant variation to generate “plant to plant variation”., and that when field conditions or farming practices introduce further variation this will increase the coefficient of variation amongst the plants. Although, the transplants population used for this experiment was grown by the same company and from the same seed stock, the individual or the subgroups of transplants were not traced back to their precise conditions or locations inside the glasshouses. The coefficient of variation at both transplant population and at final harvest was very similar so they concluded that final harvest is largely determined at transplanting stage. However, the transplants that were sampled at transplanting were different from the heads that were sampled at harvest, so there is no enough certainty that this final yield variation (co-efficient of variation) resulted from transplants variation or from other factors.

The practical aim of applying yield and ECa maps to fields is to ultimately reduce the number of samples needed to spatially characterise soil edaphic factors that control the yield.This approach would reduce the reliance on intensive grid sampling for measuring multiple soil properties through determining the appropriate sampling design for the specific crop and soil studied (Corwin *et al*., 2003)

Variable results have been obtained from studies that examined the correlation between soil factors and ECa (or yield and ECa). Walter *et al*. (2015) found no correlation in peatland between peat properties or the degree of decomposition and the EC measurements. Stadler *et al.* (2015) found a strong correlation between ECa and soil texture and moisture. Meanwhile, De Benedetto *et al*., (2000), found a strong correlation between ECa and clay content. De Benedetto *et al*., (2000) also noted that in some fields, soil conductivity is determined by a combination of soil factors such as salts, moisture, mineralogy and temperature, but in other fields, sometimes one single soil factor can control ECa measurements even if another factor is the main reason for soil or crop variation (Benedetto *et al*., 2000). This means the outcome or the interpretation of ECa scans is dependent on soil type. Zhu and Doolittle (2010) found that the optimal use of the scanning technology depends on the properties of the target soil. The authors stated that no single survey was adequate for obtaining the optimal soil map for the investigated area, instead, a combination of repeated scans that take into account the depth to bedrock and terrain attributes provide better accuracy for the map (Zhu and Doolittle, 2010).

1.7 Conclusions from the literature review

Previous research into precision farming applications relied considerably on using maps of soil physicochemical properties and particularly soil apparent electrical conductivity (ECa) and more on yield maps. However, the interpretation of the relationship between yield maps and soil maps has proved complex or challenging.

Soil ECa scans were found to have inconsistent relationship with crop yields where they proved useful only in scenarios where the soil factors that are controlling the soil's electric conductivity are the same factors that are influencing the crop yield.

Most of these studies focused on long season combinable crops where yield mapping is enabled by GPS aided sensors that can record the yield at harvest. Whereas, in manually harvested crops such as lettuce, this is not possible yet as the yield mapping systems of this crop and similar crops are not developed yet.

The studies that tackled the variability of yield in field lettuce had mostly very limited data on the associate soils, their status and their uniformity. The studies also overlooked the variability in propagation conditions relying mostly on the fact that the transplants are grown from the same genetically uniform seeds or sown on the same date. The studies that tackled soil variability for lettuce have mostly investigated the heterogeneity of soil water availability across the field and the effect of variable water supply on lettuce production while providing very little information on field variation and plants uniformity. Meanwhile, in other studies, it was established that differences in transplant sizes and date of emergence have significant impact on the final yield. Other studies have demonstrated the complex relations and interactions amongst soil properties that control crop production and how variability in one soil property can affect other soil factors across the field and which would in turn affect crop response to these factors and the demonstrated the difficulty in isolating crop response to individual soil factors in field conditions.

In this study, an attempt to map lettuce yield will be carried out whilst collecting systematically data on the underlying soil properties to identify the most influential factors on lettuce yield. The effect of a limited number of the key factors will be examined further. ECa Scans will be used as a guide for field variation. The relationship between soil ECa scans and lettuce yields will be examined whilst also examining the variability in lettuce transplants during the propagation stage that are genetically identical and commonly described as uniform for commercial production.

1.8 Objectives of the research and the central hypothesis

The central hypothesis for this study is:

“There are underlying physiological and edaphic factors that control the spatial variability in lettuce field”

This literature review has identified the following areas where further investigation is needed:

- What are the overall sources of variation in the yield of field lettuce?
- Can yield be classified for spatial or temporal management zones using ECa scans?
- Can ECa scans be used to predict lettuce yield?
- To what extent ECa scans can be used to identify soil variation for lettuce production?
- What are the key underlying soil properties that influence lettuce yield distribution?
- How do / does this / these identified factor affect the yield response?
- Can maps of other soil properties be used to inform precision management decision for lettuce crops?
- What is the extent of variability amongst lettuce transplant within the propagated trays?
- Does this variability follow a certain pattern?
- Does this particular variability continue to the field and the final yield?
- Does the variability in the physical placements of the uniformly grown transplants and which occurs due to machinery error of poor soil preparation in the field, result in variability in the marketable lettuce heads?.

1.9 Thesis Map

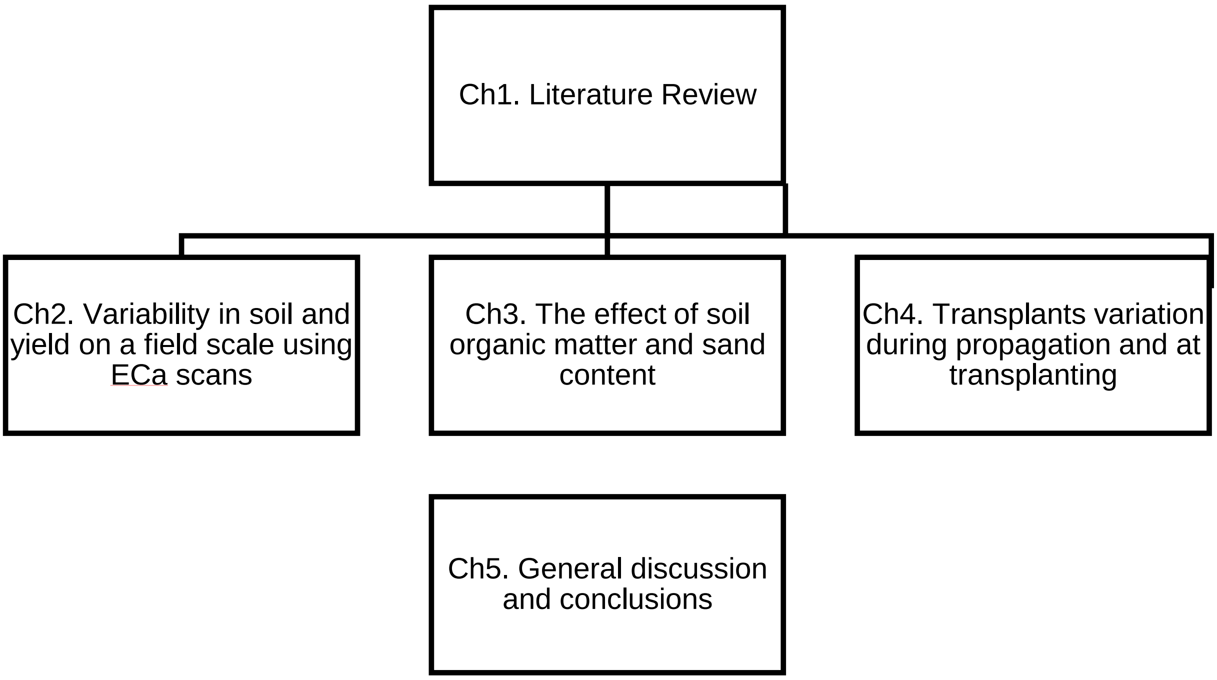


Figure 1.13. Whole thesis map

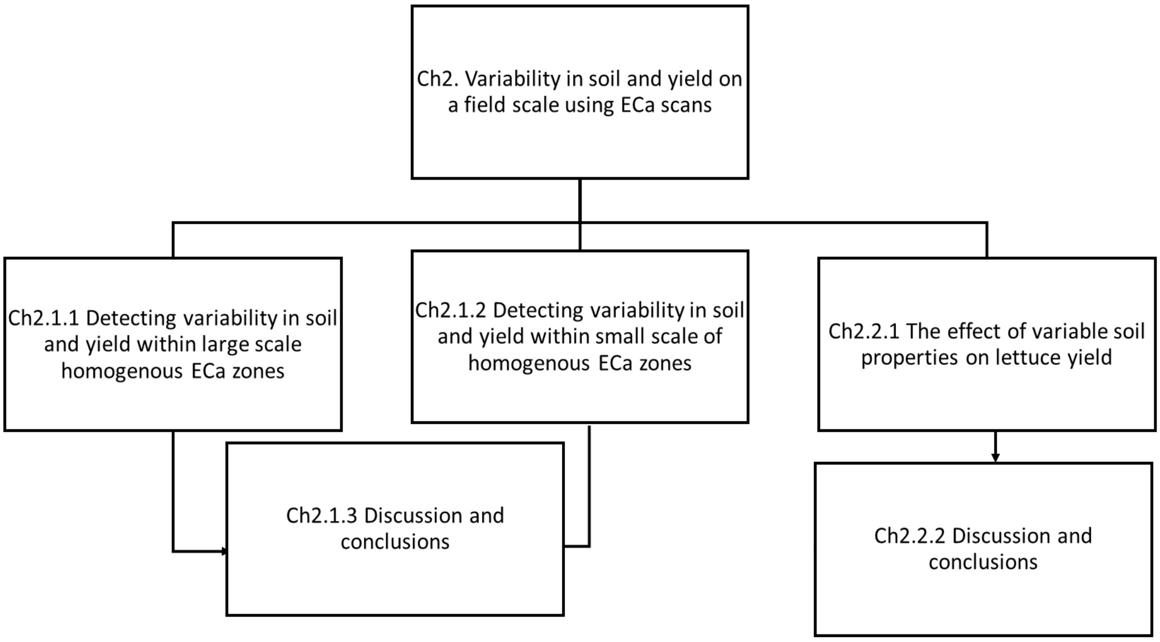


Figure 1.14. Chapter 2 map

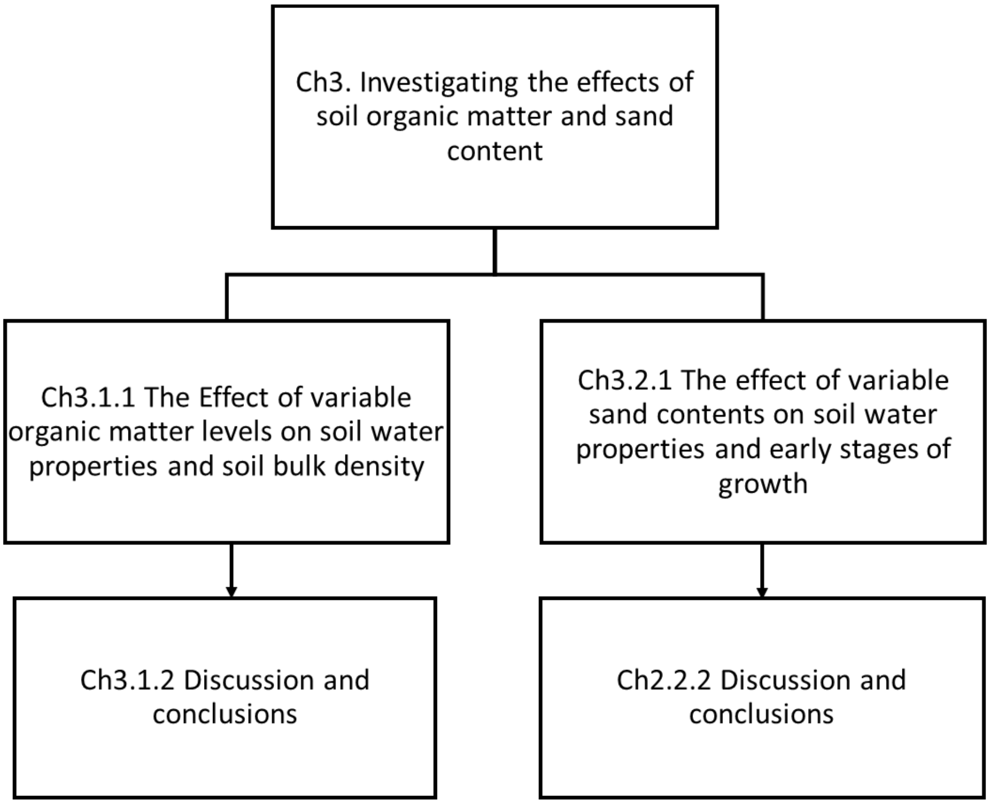


Figure 1.15. Chapter 3 map

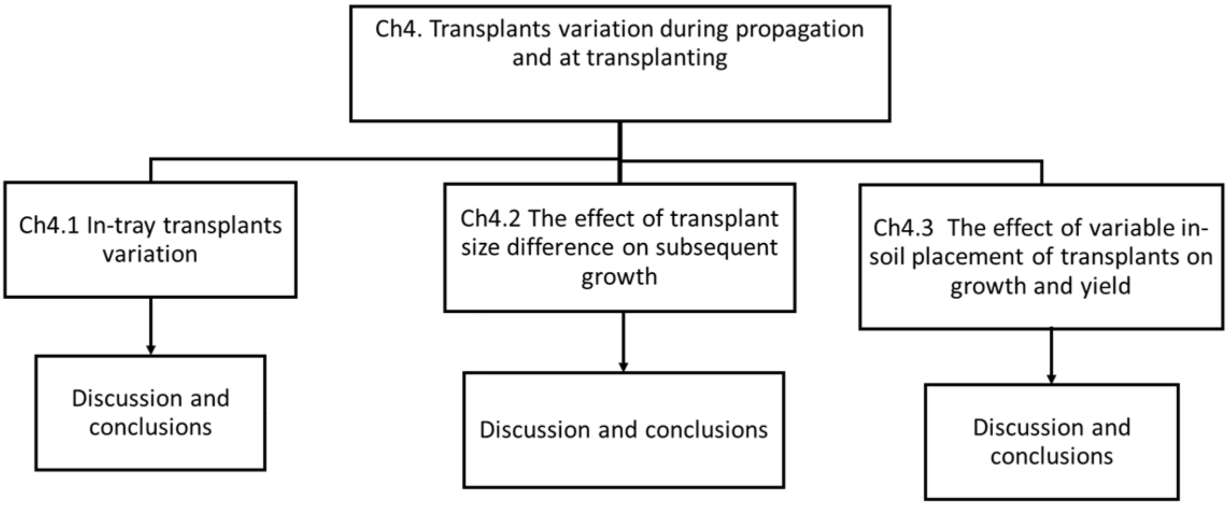


Figure 1.16. Chapter 4 map

2 Chapter 2: Variability in soil and yield on a field scale using ECa scans

2.1 Experiments FT1 and FT2: Introduction

In-field soil variability can affect lettuce (*Lactuca sativa*) uniformity of growth and maturity at harvest. The influence of edaphic factors on lettuce productivity and quality have been examined in a number of studies (Zink and Yamaguchi, 1962; Costigan, *et al*., 1983; Costigan and McBurney, 1983; Gallardo *et al*., 1996, Hoque *et al*., 2008, Luna *et al*., 2012; Kerbiriou *et al*., 2013 and M'hamdi *et al*., 2014). The effect of variation in soil edaphic factors on the variation in yield on a field scale has been reported for several long-season crops such as cereals (Stafford *et al*., 1996) and cotton (Corwin *et al*., 2003) with little published material of similar focus on short season crops such as lettuce. In addition, studies of precision agriculture have predominantly focused on cereal crops with little attention to short season or salad crops. Yield mapping of cereals and combinable crops has been enabled through grain quantity-flow sensors that can be fixed onto the combine. However, lettuce is manually harvested due to the sensitivity of this crop to handling and mechanical damage (Ryder, 1999) and the equipment to map the yield of this crop is not fully developed yet. This makes identifying its spatial variability difficult.

Variability in soil properties can be detected using soil apparent electrical conductivity (ECa) measurement (Corwin and Lesch, 2005; Ma *et al*., 2011; Grisso *et al*., 2009; Zhu *et al.*, 2010; Doolittle and Brevik, 2014). Spatial soil variability can be mapped indirectly by scanning the field soil for electric conductivity (ECa) then demarcating zones for efficient targeted sampling (James *et al.* 2003; Earl *et al*., 2003) or in some cases demarcating homogenous field zones in terms of yield and soil (Taylor *et al.,* 2003). Therefore, the relationship between soil properties and soil electrical conductivity (ECa) has been established and the potential for using ECa soil scans to predict yield variation in long season crops has been reported. However, results have been inconsistent and vary with both the crop type and the key factor that determines the optimum yield for that crop (Corwin *et al*., 2003 and Corwin and Lesch, 2003). Panagopoulos *et al*. (2006) related reduced lettuce yield to zonal soil problems within the field, such as a problem with the hydraulic conductivity in some areas of the field and the existence of a zone with low permeability, without identifying an optimum yielding zone for lettuce. However, the predicted yield correlated with the final yield provided that some spatially restricted amendments were carried out.

In-field variation is a common problem for head-lettuce growers (Wurr *et al.,* 1992) as variable sized heads are not commercially desirable and this variability might additionally extend to other postharvest quality. Uniformity of crop growth is very important for achieving an optimum marketable yield that is suitable for a single pass harvest (Wein, 1997). Agricultural practices and growing conditions in the field play a key role in achieving the required lettuce yield and hence, uniformity.

Lettuce crops tend to produce a specific head density under specific environmental conditions, which usually persists to maturity and harvest (Wurr *et al.,* 1992). Favourable yield responses in lettuce can be achieved when standard agronomic inputs are manipulated, indicating a potential for reducing lettuce variation qualitatively and quantitatively through variable inducements / inputs (Gallardo *et al.,* 1996; Newman *et al.,* 2005; Luna *et al.,* 2012 and Kerbiriou *et al.,* 2013). Therefore, the soil variation that affects the uniformity of head development and maturity in lettuce, affects in turn the efficiency of the harvest.

Variable crop management decisions for field grown Iceberg lettuce, using maps of soil electrical conductivity (ECa) require identification of the sources and scales of variation. In experiments FT1 and FT2, the main aim of using commercial soil electric conductivity scans (ECa maps) was to keep the sampling intensity commercially relevant and beneficial to practical farming situations and to minimise the time and cost spent on direct and intensive soil sampling and analysis. Several earlier studies used ECa scans for targeted sampling in the field as these scans coincide normally with soil variation (Doolittle and Brevik, 2014; Grisso *et al*., 2009; James *et al*., 2003; Taylor *et al*., 2003; Earl *et al*., 2003).

The aims of the experiments: the aims of the experiments FT1 and FT2 were:

- Identify variable management zones using ECa scans
- Determine the variability in soil properties between zones of different ECa ranges
- Determine the variability in plant growth and development between zones of different ECa ranges.
- Examine the scale of the variability of ECa zones at which variable management decisions could be informed.

Null Hypotheses:

1. Field zones identified using ECa maps do not vary in yield.
2. Field zones identified using ECa maps do not vary in soil properties.
3. Small scale zones with variable ECa values do not vary in soil properties.

2.1.1 Field Experiment FT1: Detecting variability in soil and yield within large scale homogenous ECa zones

2.1.1.1 Introduction to data

Soil ECa maps were used for carrying out targeted sampling in order to understand their influence on variability in marketable lettuce yields. The first field experiment identified three zones within the field using the soil electric conductivity (EC) scans by dividing the raw scanning data into three ranges; low, medium and high. This experiment (FT1) was done to detect homogenous soil ECa zones within the field guided by soil ECa scans. This was followed by an attempt to relate the yield response to a limited number of edaphic factors that varied amongst this zone in addition to ECa ranges.

Null Hypotheses:

1. Field zones identified using ECa maps do not vary in yield.
2. Field zones identified using ECa maps do not vary in soil properties.

2.1.1.2 Data and Methods

a) Site specifications

The studied field (Redmere P36) is located in Ely, Cambridgeshire, UK (52°26’44.86” N, 0°25’08.56” E). The field comprises 2.15 ha within an 8.45 ha worked area (other cropped fields) (Figure 2.1).

Figure 2.1. Location of the study site (Redmere P36) in Ely, Cambridgeshire, UK (source: Google Maps).

The soil in Redmere P36 is classified as loamy and sandy with peaty texture at the surface and naturally high ground water (Thompson, 2007). The studied crop received a total of 81 mm precipitation and an average temperature of 15.8 °C, over the crop cycle (22.2 °C maximum and 9.6 °C minimum). The crop was grown using standard practices in regard to weed, pest and disease control and received the standard commercial agronomic inputs applied uniformly (soil indexes are presented in Table 2.1). Field crop rotation is shown in Table 2.2.

Cropping details:

The field was used to grow two commercial crops of iceberg lettuce (*Lactuca sativa* var. Antarctica). FT1 lettuce were transplanted on around 6th May 2014 and harvested 29th June 2014 (56 days).

Lettuce transplants were planted commercially using a mechanical transplanter (Regero, France). Plant spacing was 30 x 30 cm for FT3 (early crop, slower growth due to lower weather temperature and solar radiation levels) and 30 x 35 cm for FT4 (summer crop, faster growth due to greater temperatures and solar radiation levels). The crops were grown following standard practice to control weeds, pests and diseases. The amounts of fertiliser applied are shown in Table 2.11. The crops were irrigated using an overhead irrigation system and according to the standard application rates and soil moisture deficits.

Table 2.1. Grower's soil report and information for Redmere P36 (May 2014).

Soil pH	Nutrient index				Available nutrient (mg/l)				Total fertiliser application for both crops (kg/ha)			
	P	K	Mg	N	P	K	Mg	N	K_2O	P_2O_5	N	MgO
6.7	3	2-	3	-	40.0	169	130	-	200.76	78.26	168.93	94.47

Table 2.2. Crop rotation for Redmere P36.

Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Crop	Turf	Potatoes	No crop	Turf	Lettuce	Celery	Red Beet	Lettuce	Wheat	Lettuce

b) ECa scans

The field Redmere P36 was scanned commercially by Fresh Produce Consultancy Ltd for soil ECa on 11 March 2014, using a Veris E3100 scanner, whilst the field was in wheat stubble. The scanner bout width for scanning was 10 – 12 m and was operated at an average of 24 m spacing between bouts and used DGPS (Differential Global Positioning System) so accuracy should be expected to be within 30 cm (Esri, 2014a).

The raw scanned data (comprising the coordinates of the data points) were processed and plotted on Google Earth to locate the ECa values on the ground and classify the data into three bands; low, medium, and high using the equal intervals data classification method, due to the suitability of this this standard method for use with continuous variables (ESRI, 2014b). The bands were then represented by three differently-coloured dots on the ground (green, yellow and red) and a zone was chosen from each ECa band for sampling (Figure 2.2). The bands and the zones were as follows:

- Green band (low ECa) 14.62 - 40 mS, containing Zone A
- Yellow band (moderate ECa) 41 - 50 mS, containing Zone B
- Red band (high ECa) 51 - 68 mS, containing Zone C

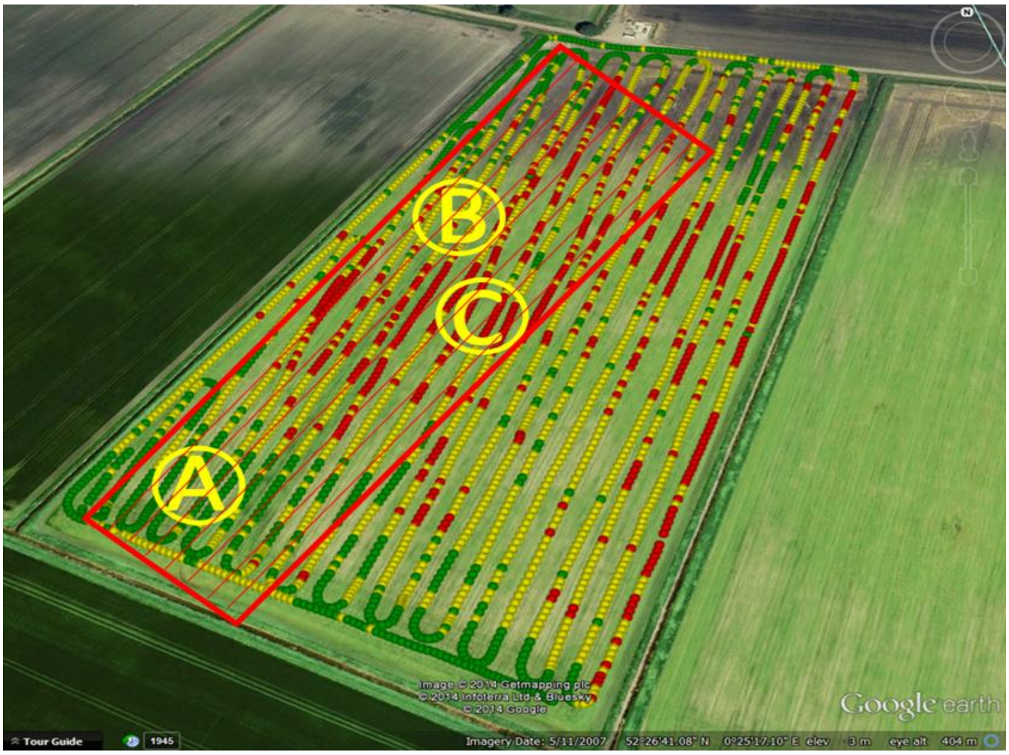


Figure 2.2. Redmere P36 field with ECa bands (green-low ECa 14.62-40 mS), yellow-moderate ECa 40-50 mS) and red-high ECa 50-68 mS) and target zones A, B and C. The thin red lines show the planting direction and the red box itself indicates the targeted area planted on the same date with the same variety (*Lactuca sativa* var. Antarctica).

c) Data collection

Zones A, B and C (Figure 2.2), were selected for sampling because each zone was located in the largest area of one of the three ECa bands. The centre point from each identified zone was marked using a GARMIN e-Trex GPS device (Garmin Europe Ltd, Hampshire, UK) of accuracy range < 3 m. Four more locations around the centre location were also marked and were 1 m distant each from the central point to provide representative samples of the zone. All five locations were sampled and means calculated.

- **Soil sampling and assessments**

Soil was sampled once at mid-growth when the crop was at the rosette stage. Soil samples were taken from each sampling location at three depths 0 - 30 cm and 30 - 60 cm and 60 - 90 cm, using soil gouge augers (EijkelKamp, Netherlands) of size 30, 60 and 90 cm in length and 40, 30 and 20 mm in diameter, respectively. At each depth, three subsamples were bulked and mixed. The samples were transferred into pre-labelled plastic bags, sealed and then taken to the laboratory at HAU where they were air dried for 2-3 weeks. The samples were broken down into a finer texture using a pestle and a mortar and passed through a 2.0 mm sieve to remove stones. The total number of soil samples was 5 locations in each zone x 3 zones x 3 depths = 45 soil samples. All soil laboratory assessments were undertaken using standard methods (Jackson *et al*., 1986). Assessments included soil texture, OM, pH, P, K and Mg for each sample (Table 2.3). The soil analysis results of each zone were then used to obtain soil indexes for the fertiliser recommendations from the fertiliser manual guide RB209 (DEFRA, 2010).

Table 2.3. Soil tests undertaken and their methods.

Soil test	Method
Soil texture	Particle size distribution
Organic matter (OM)	Loss on ignition
Acidity level (pH)	Measuring the pH in soil suspension extracted by water using pH-meter
Phosphorus (P)	Extracting soil using sodium bicarbonate solution then measuring spectrophotometrically (Perkin Elmer AAnalyst 200, PerkinElmer, Inc. Connecticut, U.S.A)
Potassium (K)	Extracting soil using ammonium nitrate and measuring the potassium amount in the filtered extract using an atomic absorption spectrophotometer (Jenway 632621, 766nm Cole-Parmer, Cambridgeshire, UK)
Magnesium (Mg)	Using the same extract for potassium, then measuring the Mg amount after adding strontium chloride using an atomic absorption spectrophotometer (Perkin Elmer AAnalyst 200, Perkin Elmer, Inc. Connecticut, U.S.A)

(Source: Adapted from ADAS, 1986)

- **Plants sampling and assessments**

Lettuces were sampled twice; mid growth and at harvest from each zone.

Mid-growth (rosette stage - 35 days after planting): From each location 10 plants (= 50 plants/zone) were taken using a sharp knife cutting at soil surface. The plants were weighed onsite using battery operated portable balance to an accuracy of 0.01 g and were placed inside sealable and pre-labelled plastic bags and transported to HAU on the same day. Additionally, the rosette diameter and the height of two heads (above the soil) at each location were measured using a steel measuring tape.

At harvest: The same pattern was followed at harvest as for mid-growth where five whole heads were taken per location using a sharp harvest knife to cut heads horizontally above soil surface, giving 25 plants per zone. The heads were harvested around 4 days before commercial harvest.

Quality assessments of the mature heads: At harvest, the whole head fresh weight (FW) was recorded on site, then the heads were transported to Harper Adams University on the same day and stored in the cold store at 4 C°. The next morning the outer leaves were removed to obtain the closed (marketable) head which was weighed as trimmed-head weight (TFW). Error in the trimming procedure was minimised by using one person for all trimming. The circumference of trimmed heads was measured using a measuring tape. The densities of trimmed heads were scored on a scale from 1 to 8 using market specifications provided by G's Fresh Ltd (Barway, UK) (Figure 2.3). Dry matter was obtained by drying the lettuce in a fan assisted oven at 80°C for a minimum of 120 hours to a constant weight. All weight data were collected using digital scales accurate to 0.01 g (KERN FKB 16K0.1, KERN and Sohn, GmbH, Balingen, Germany).

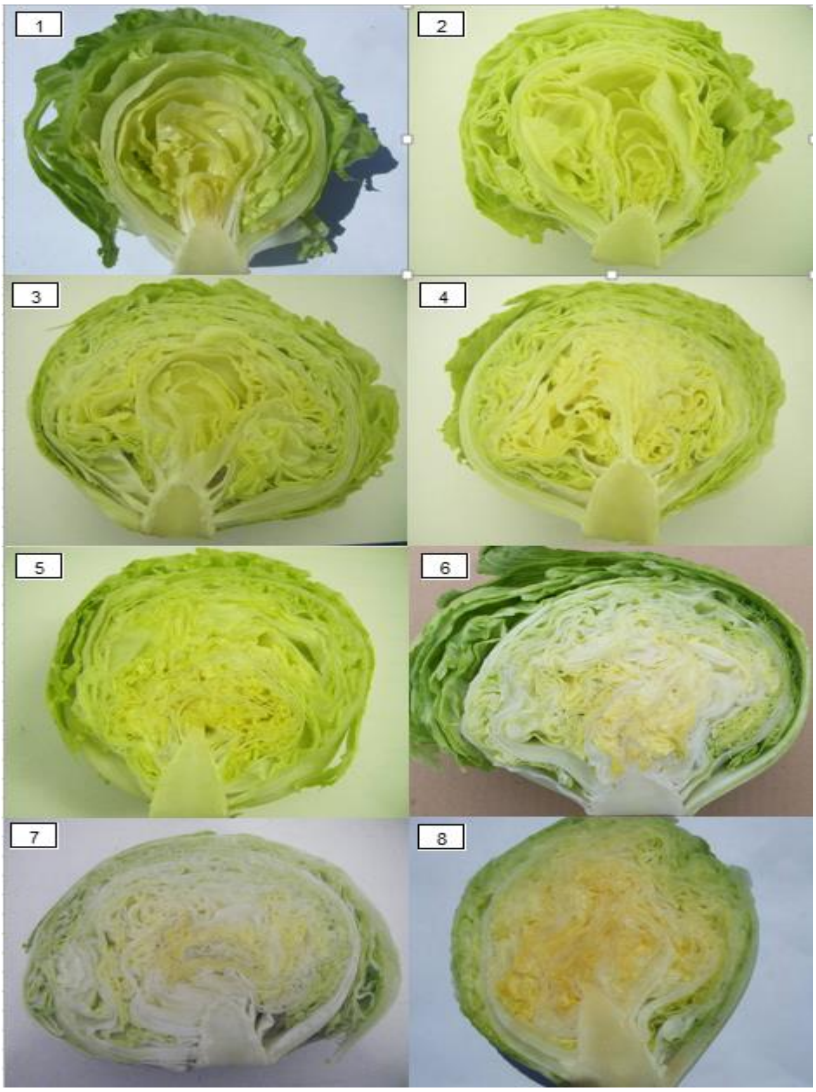


Figure 2.3. Tesco market specifications guide for head density scoring scale from 1 (low) to 8 (high). (Source: G's Fresh Ltd)

2.1.1.3 Statistical analysis

The experimental design and the sampling density of the first field experiment (FT1) was distributed as shown in Figure 2.4. This experimental design took into account several factors such as field size, the scale of the ECa variation, GPS accuracy range, grower choices of variety and planting dates in addition to other practical limitations. Having the same lettuce variety and planting date (the largest part of the field planted with the same variety on the same date) was particularly important to minimise the variation resulting from differences between varieties.

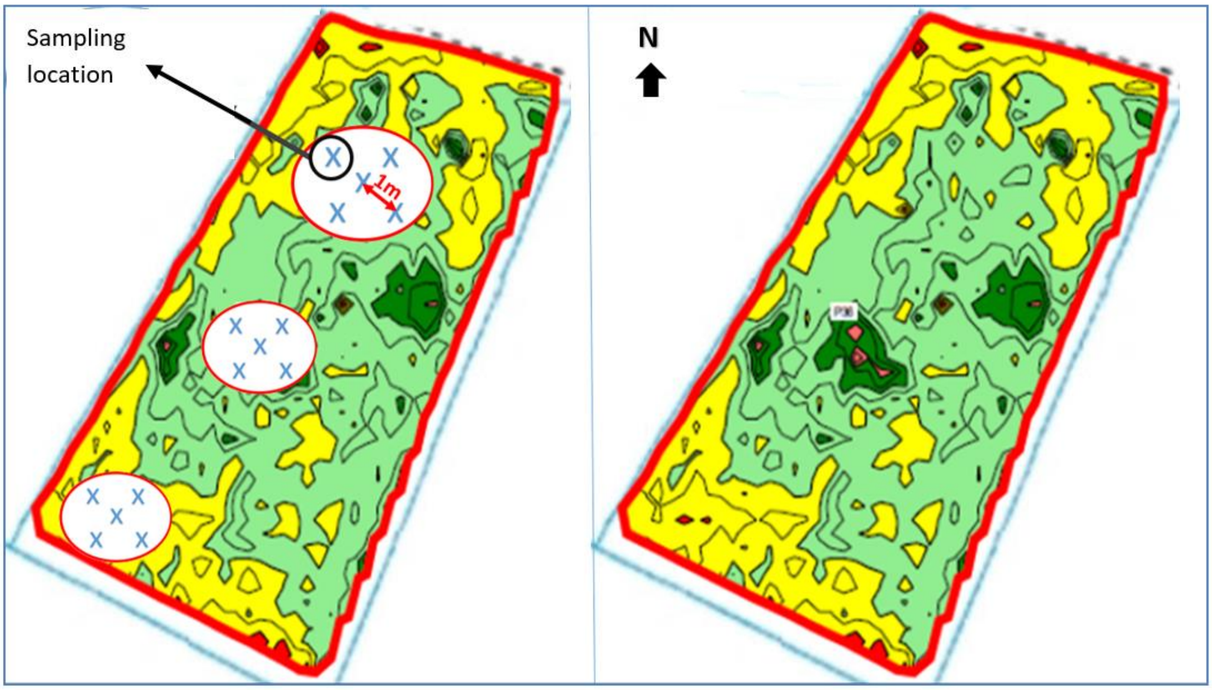


Figure 2.4. Sampling pattern showing the three zones (A, B and C) and the sampling locations (X) in each based on ECa maps performed commercially using the scanning raw data.

To test each ECa band (zone), five locations were selected within each zone. Each location was initially set to be treated as a replicate. It was difficult to replicate the zones within the same field in practice, due to the natural variation in field conditions and as other parts of the field were planted with mixed varieties on different dates and had different soil ECa levels. The data were analysed using ANOVA in Genstat (16th edition, VSN International, Hemel Hempstead, UK) with zones as a treatment (n=50 or n=25 depending on the assessments). Additionally, multiple comparisons procedure that relied on Tukey test was used to identify the places of significance. A limitation of this approach was that there was a lack of real replication and as such the potential for pseudo replication. However, the data were treated as preliminary and used to identify trends of interest for subsequent experiments. A correlation matrix that utilised standard Pearson correlation coefficients was produced for the correlation between the whole head fresh weight, trimmed head fresh weight and the measured soil properties.

2.1.1.4 Results:

Field observations: The variable leaf surface area, growth and weed infestation were visible between the zones at mid growth. Zone A for example, which had the lowest ECa value, had a substantial weed infestation, small heads with little leaf surface area (LSA) or crop cover (Figure 2.5, Zone A). Whereas, Zone B in the medium ECa band, had larger heads and better crop cover (LSA) in comparison to Zone A, with much less or negligible weed presence (Figure 2.5, Zone B). Zone C was very similar to Zone B.

Figure 2.5. Visual observation of plant growth and leaf surface area of two different zones (A and B) in the field as identified using the ECa map. Arrow indicates weed? (Source: Author's own)

- **Fresh weight at mid growth and at harvest:**

The whole fresh rosette weight at mid-growth showed significant ($P<0.05$) differences between the three zones. Lettuce from Zone A had a significantly lower fresh weight than lettuce from Zones B and C, both at mid-growth and at harvest (Figure 2.6). Lettuce fresh weights from Zone B and Zone C were significantly different from each other at mid growth, where, Zone C had the greatest fresh weight. There was no statistical difference between lettuce from Zone B and C at harvest, however, they were both significantly higher in fresh weight than lettuce from Zone A (Figure 2.6).

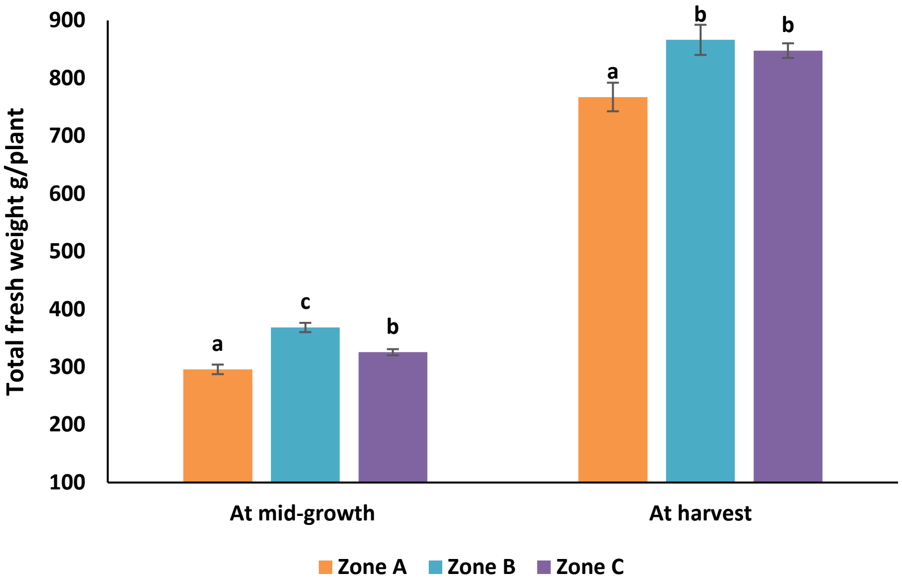


Figure 2.6. Total fresh weight of the three zones at mid-growth (n=50) and at harvest (n=25). Error bars show +/- one standard error of the mean. Lower case letters are used to signify statistical difference and where lower-case letters differ, values are significantly different (P < 0.05).

- **Trimmed head weight at harvest (marketable yield):**

To normalise the trimmed head fresh weight data, they were transformed using log base 10 and the statistical analysis here was undertaken on logged data. A strong correlation was found between the total head fresh weight and the trimmed head fresh weight (Figure 2.7).

Similarly, to the total fresh weight, Zone A had the lowest trimmed head fresh weight amongst the zones and varied significantly from Zone B and Zone C. However, there was no significant difference between Zones B and Zone C in trimmed heads fresh weights (Figure 2.8). Although there were no significant differences in fresh weight or marketable weight between Zone B and Zone C, Zone B had greater total fresh weight but less trimmed-head weights and less dry matter than zone C.

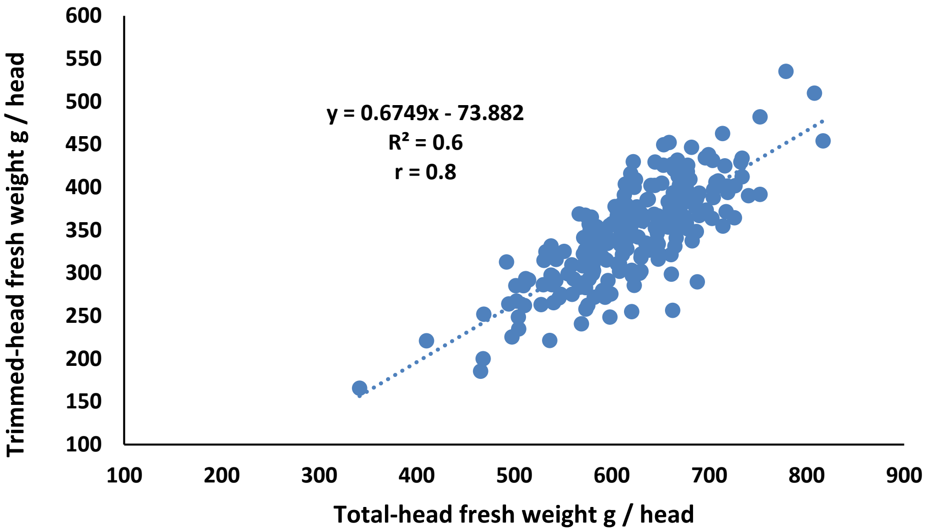


Figure 2.7. The relationship between trimmed head fresh weight and total head fresh weight. Pearson's correlation coefficient (r) is indicated.

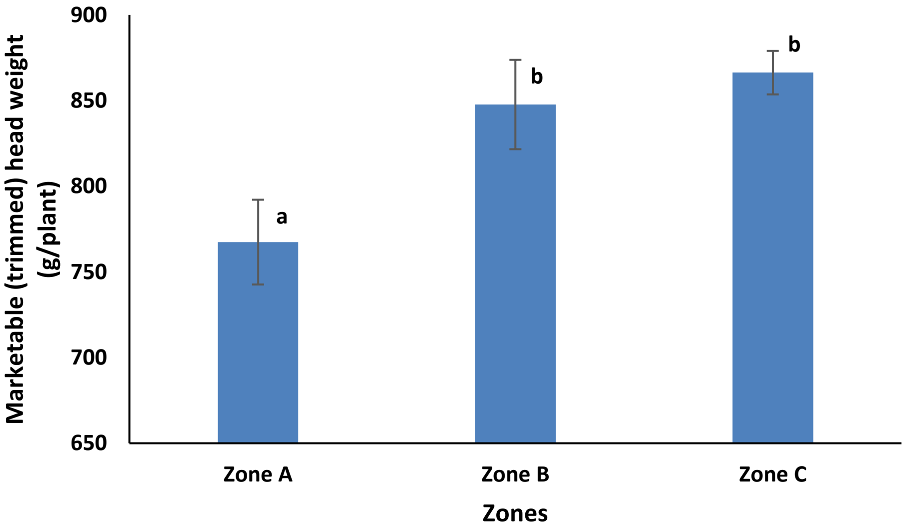


Figure 2.8. Marketable (trimmed) head weights of the three zones at harvest (n=25). Error bars show standard error for samples n=5, where lower case letters differ, values are significantly different (P <0.05).

- **Dry weight at mid-growth and at harvest**

Dry weight data at harvest showed similar results in significance to the whole head and trimmed head fresh weight results at harvest (Figure 2.9). Mid-growth results however were different. Zones A and B varied significantly from each other at mid growth but neither one of them varied significantly from Zone C (Figure 2.9) unlike mid growth fresh weight where all three zones differed significantly from each other (Figure 2.6).

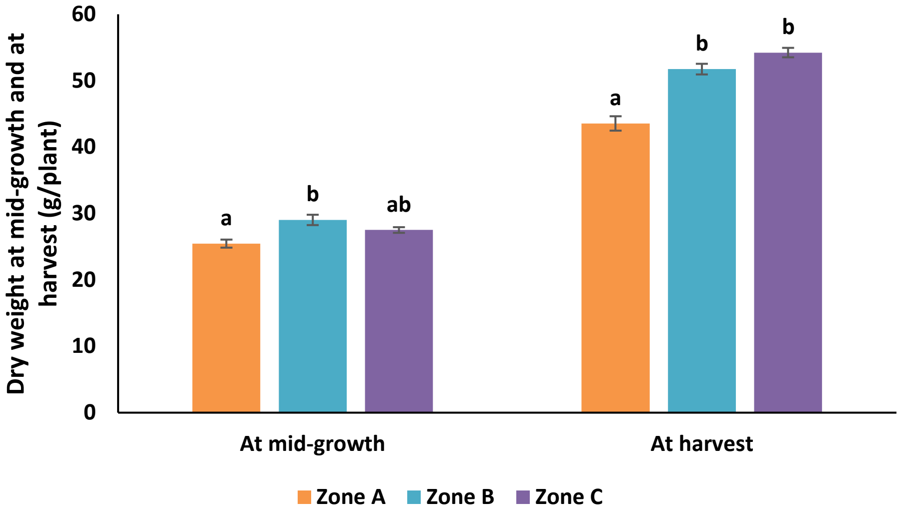


Figure 2.9. Dry weight at mid growth and at harvest (n=25, P<.001). Error bars show standard error for samples. Where lower case letters differ, values are significantly different.

- **Rosette dimensions at mid-growth**:

Zone B had significantly better growth in comparison with Zone A and C. Both diameter and height of rosettes were larger in Zone B. Zone C and A only differed significantly in diameter (Figure 2.10), with Zone A having the lowest rosette diameter.

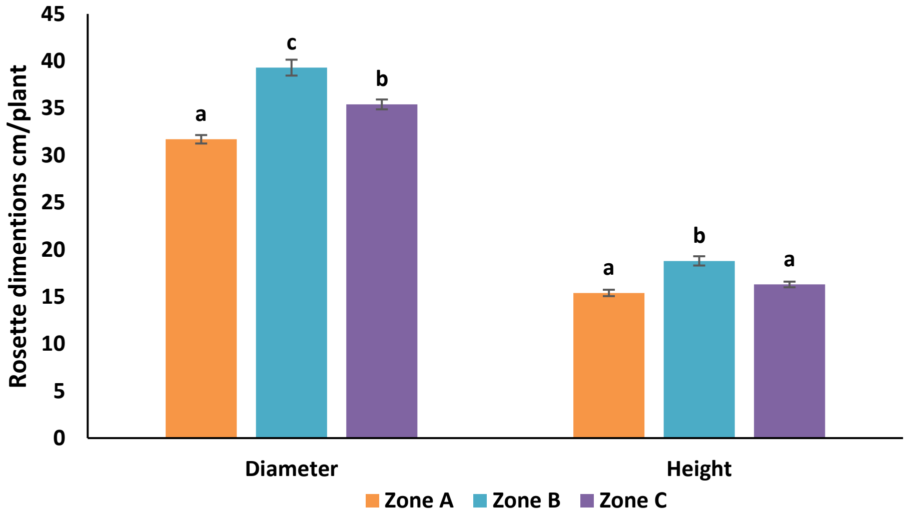


Figure 2.10. Rosette dimensions (diameter and height). Error bars show standard errors for the samples (n), rosette diameter, rosette height (P<.001, n=10). Where lower case letters differ, values are significantly different.

- **Trimmed head circumference and density**:

Calculating head density based on trimmed head weight circumference and trimmed head fresh weight gave no significant differences between the zones (data not shown). However, using the market specification guide for density scoring showed that Zone C had significantly greater density than Zones A and Zone B (Figure 2.11). There were no significant differences in the trimmed head circumference amongst the three zones (data not shown).

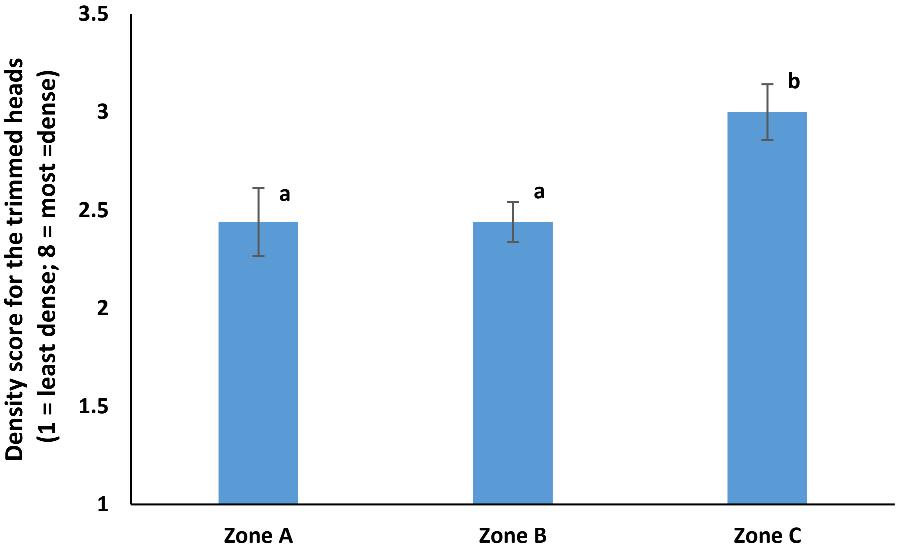


Figure 2.11. Trimmed-heads density score for samples (n=25). Error bars show standard error for samples (n=25) where lower case letters differ values are significantly different (p<0.05).

- **Soil assessment results**

Organic matter

The organic matter percentage was very high in all three zones; the significantly lowest mean ($P < 0.001$) was for Zone A (39.3 % OM),whereas the organic matter in Zones B and C were significantly greater (51 % and 47 % respectively) but they did not differ significantly from each other (Figure 2.12).

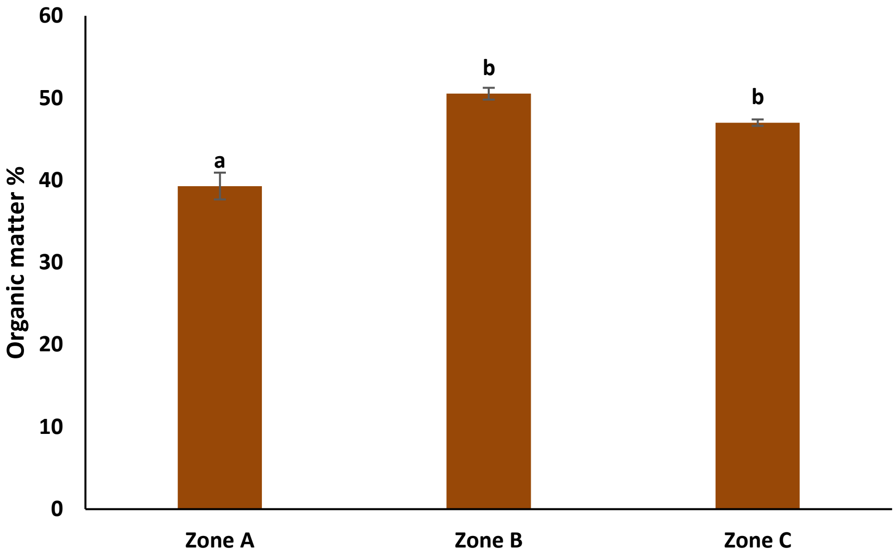


Figure 2.12. The difference in OM percentage between the zones (n = 5) error bars show standard errors for samples (n = 5). Where lower case letters differ, values are significantly different ($P < 0.001$).

The percentage organic matter content found in the three zones indicated that the soil classifies as peaty soil (Natural England, 2008). However, the particle size distribution of the mineral fraction of the soil, soil texture, was also examined for further comparison amongst the studies zones.

Texture

The soil texture triangle (Natural England, 2008) was used to classify the mineral fraction of the soil into standard soil types. The soil in general was relatively high in clay (above 33 %). Zones A and B were classified as silty clay loam at the three sampling depths. However, Zone C was classified as silty at the surface, silty clay loam in the subsoil (up to 60 cm) and silt loam in the deeper horizon at 60-90 cm (Table 2.4). Although, the identified soil types were similar, the proportion of the sand, silt and clay as calculated and averaged between the samples of each zone and each depth showed clearer differences (Table 2.4).

Table 2.4. Soil type for the mineral fraction of the soil, and the percentages of sand, silt and clay of each zone averaged between the samples (n=5) for each depth.

Zone	**Depth**	**Soil type**	**Sand %**	**Clay %**	**Silt %**
A	0-30cm	silty clay loam	14.2	32.9	52.9
	30-60cm	silty clay loam	8.5	35.6	56
	60-90cm	silty clay loam	6.6	29.8	63.5
B	0-30cm	silty clay loam	20	37.2	42.8
	30-60cm	silty clay loam	7.9	33.4	58.6
	60-90cm	silty clay loam	17.3	29.2	53.5
C	0-30cm	silty clay	5.5	42.8	48.5
	30-60cm	silty clay loam	14.5	32.4	53.1
	60-90cm	silt loam	20	53.5	58.8

Analysis of variance for silt content and sand content of the three zones showed no significant differences. However, in terms of the clay content, it showed that Zone A was significantly lower in clay that Zone C ($P < 0.05$) with Zone B having no statistical difference from either A or C, (Figure 2.13).

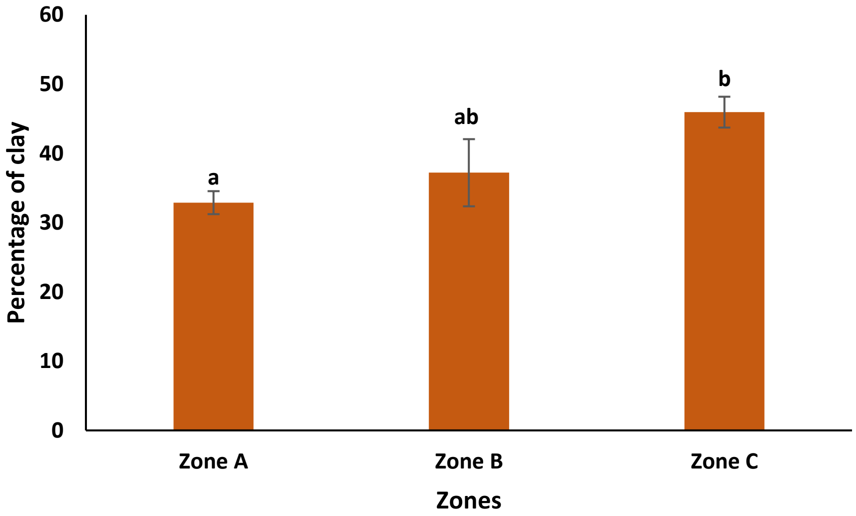


Figure 2.13. The difference in clay proportion between the zones at 0 – 30 cm depth, for (n=5). Error bars show standard errors for samples (n=5). Where lower case letters differ, values are significantly different ($P<0.05$).

Soil pH, nutrients and soil-indexes

There were no significant differences in soil acidity/alkalinity (pH) amongst the three zones. Soil pH values for the three zones ranged between 7.4 for Zones A and C to 7.5 for Zone B.

- *Magnesium*, Zone A was significantly the highest in Mg content, Zone B was the lowest and Zone C between these two (Figure 2.14).

- *Potassium*; Zone A was again the highest in K, with Zone B and Zone C significantly lower in this nutrient with no difference between each other (Figure 2.14).

- *Phosphorus*; All the zones varied significantly in P content, with Zone C being significantly the lowest in P content and Zone B the highest, and Zone A was in the middle (Figure 2.14).

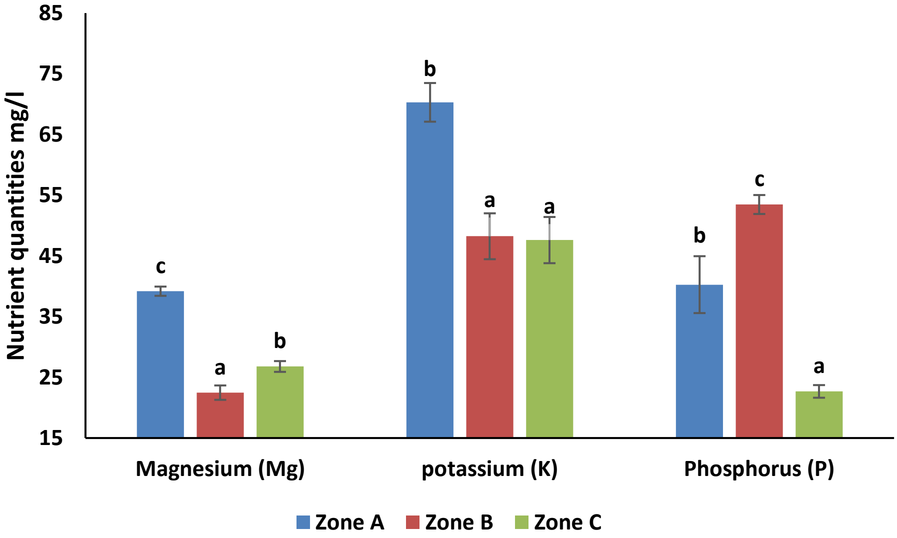


Figure 2.14. Mg, K, and P concentrations in the soil of the three zones (A, B and C) for soil samples (n=5) error bars show standard errors of the samples (n=5). Where lower case letters differ, values are significantly different (P<0.001).

Variable nutrient concentrations resulted in different indexes for fertilisers recommendations (DEFRA, 2010). These indexes are presented in (Table 2.5).

Table 2.5. Soil indexes for the analysed nutrients of each zone as well as mg / L values

	Indexes			mg / L values		
Zone	Mg index	K index	P index	Mg mg / L	K mg / L	P mg / L
A	1	1	3	337.9	367.0	25.6
B	0	0	4	200.0	250.0	34.1
C	1	0	2	233.2	249.0	14.3

- **Correlation matrix and potential relationships**

The trimmed head fresh weight (TFW) has significantly correlated with soil magnesium content, whereas, FW was correlated with organic matter, magnesium and potassium content. Both magnesium and potassium were significantly correlated with organic matter (Table 2.6).

Table 2.6. Correlation matrix for FW, TW and soil factors (n= 15)

	OM (%)	Mg (mg/L)	K (mg/L)	P (mg/L)	pH	FW (g/plant)	TW (g/plant)
OM	1						
Mg	-0.85**	1					
K	-0.78**	0.85**	1				
P	0.07	-0.13	0.14	1			
pH	0.18	0.12	0.34	0.04	1		
FW	0.61*	-0.62**	0.62*	-0.04	0.38	1	
TW	0.25	-0.54*	-0.50	-0.01	0.47	0.47**	1

* $P < 0.05$

** $P < 0.001$

2.1.2 Field Experiment FT2: Detecting variability in soil and yield within small scale of homogenous ECa zones

2.1.2.1 Introduction to data collection

In Experiment FT1, the soil ECa zones that were examined were relatively rounded shaped areas with a minimum of 4 m in diameter each. More information was needed about the spatial variability of the studied field than could be obtained from the available ECa scans and their raw data such as the spatial variation in a different part of the field and whether smaller scale zones of homogenous ECa ranges would mean variability to the soil and the crop. An additional reason for testing smaller zones of ECa was that smaller zones of homogenous ECa zones are easier to find in the field and this allows better replication which was not possible in FT1.

Null Hypotheses:

1. Small scale zones with variable ECa values do not vary in soil properties.

2.1.2.2 Materials and Methods

a) Site

FT2 was undertaken on the same site as in FT1 (Redmere P36). Similarly, to FT1, several factors were considered when choosing the section of the field in which the experiment was to be incorporated, such as field size, the scale of the ECa variation, GPS accuracy range, as well as grower choices of variety and planting dates. Therefore, FT2 was laid out within (lettuce cv. Kuala cru) a planting pull of 6 rows / beds of plants, where each row was 8 m. Therefore, for this field a planting pull width was 6 x 8 = 48 m). This crop had received a sum of 40.8 mm precipitation and an average temperature of 14 °C degree over the crop cycle and similarly, to FT1, this crop received the standard weed, pest and disease control practices uniformly, as well as the nutrient required (soil indexes and the fertilizers applied are presented in Table 2.7.

Table 2.7. Grower's soil report and information for Redmere P36 July 2014

Soil pH	Index				mg/l (Available)				Total fertilizers applied for both crops (kg / ha)			
	P	K	Mg	N	P	K	Mg	N	K2O	N	P2O5	MgO
6.7	3	2-	3	-	40.0	169	130	-	141.4	106.82	106.82	94.47

Cropping details:

The field was used to grow two commercial crops of iceberg lettuce (*Lactuca sativa* var. Antarctica). FT2 lettuce (*Lactuca Sativa* var. Kuala cru) were transplanted around 18th August and harvested on around 8th October 2014 (~ 52 days).

Lettuce transplants were planted commercially using a mechanical transplanter (Regero, France). Plant spacing was 30 x 30 cm for FT3 (early crop, slower growth due to lower weather temperature and solar radiation levels) and 30 x 35 cm for FT4 (summer crop, faster growth due to greater temperatures and solar radiation levels). The crops were grown following standard practice to control weeds, pests and diseases. The amounts of fertiliser applied are shown in Table 2.11. The crops were irrigated using an overhead irrigation system and according to the standard application rates and soil moisture deficits.

b) ECa scans and data collection

Using the same raw data of the scans that were used in FT1, ECa data were re-banded into new ranges of ECa to determine sampling zones. It was necessary to change the bands studied due to moving into a new part of the field with different ECa values and a smaller scale of variation. These maps were created using the same methods for FT1 ECa maps. Bands were allocated using equal intervals classification method, similarly to FT1. The bands were also represented using distinctively-coloured dots on the ground (Figure 2.15) and they were as follows:

ECa - Band1 GC (symbolised on the map by green dots) = low conductivity; ECa 9.1 - 24.9 mS.

ECa - Band2 BC (symbolised on the map by blue dots) = medium conductivity; ECa 25 - 29.9 mS.

ECa - Band3 RC (symbolised on the map by red dots) = high conductivity; ECa 30 - 57.1 mS.

To increase the number of samples, each range (band) was sampled at seven locations instead of five as in FT1. These replicated locations are shown with arrows on the map numbered from 1 to 7 for each colour (Figure 2.15).

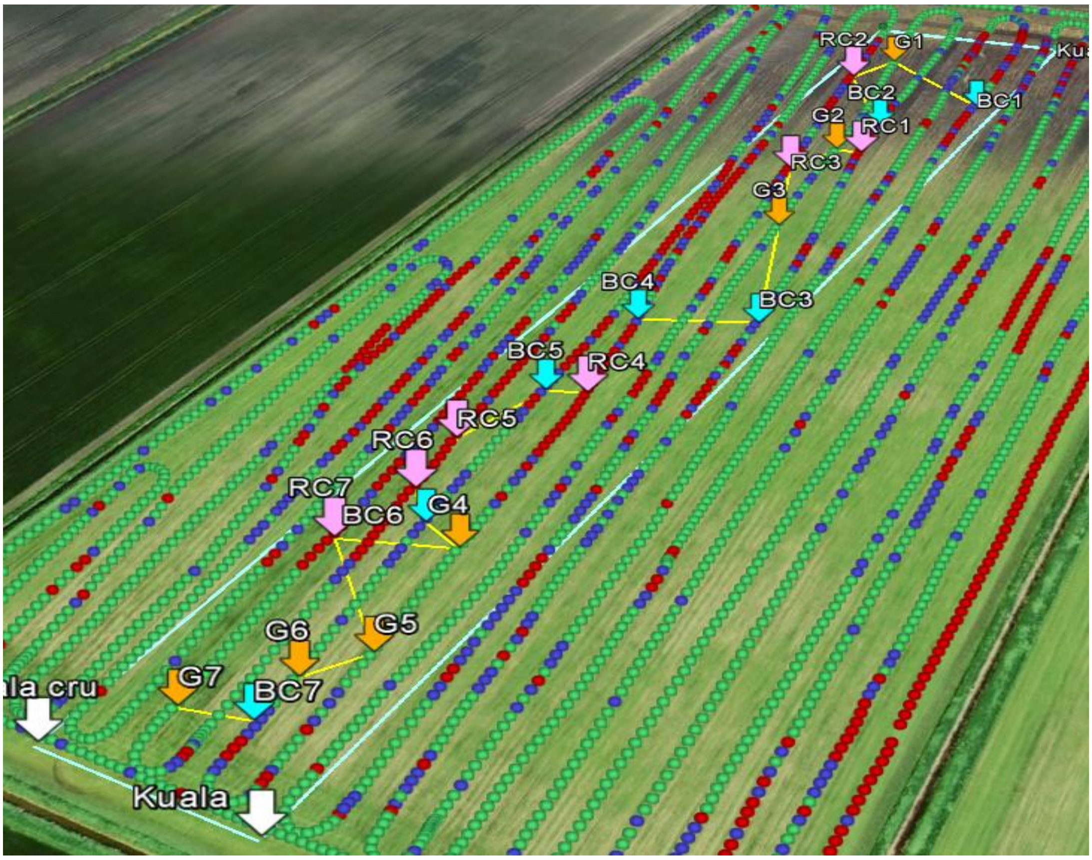


Figure 2.15. sampling design for FT2. Sampling locations that belong to the same ECa range are indicated by arrows of the same colour. Yellow lines on the grounds are the distance between locations. The light blue box on the ground is the variety planting pull (same planting date).

c) Soil sampling and assessments

Soil was sampled once at mid growth (35 days after planting) using hand soil auger size 30 cm in length and 40 mm in diameter. One sample was collected at 0-30 cm depth from each location, each consisted of three subsamples that were mixed together inside a sealed bag giving seven samples per band and 21 samples in total. Assessments were undertaken using the standard methods as in FT1 and included texture, organic matter and pH.

d) Crop sampling and assessments

The crop was sampled three times during its life cycle; Early stage (14 days after planting), Mid-growth (35 days after planting) and Late stage or maturity (3 days before commercial harvest).

- ***Early stage,14 days after planting (14 DAP)***

  Ten young plants were sampled at each location and transferred to HAU for further assessments, which included:

  - ✓ All visible leaves were counted from the oldest to the youngest
  - ✓ Fresh weight (FW) was recorded the morning following sampling (plants were put in the cold-store overnight).
  - ✓ Dry weight (DW) was obtained after drying the young plants in the oven at 80 °C for a minimum of 120 hours.

- ***Mid-growth, 35 days after planting (35 DAP)***

Ten plants were sampled at each location and transported to HAU on the same day for assessing FW and DW following the same protocol as in the sampling at the early stage of growth.

- ***Late stage (maturity)***

Ten whole heads where harvested and assessed at each location, following the same procedures and methods that were followed in FT1 yield assessments. In addition to measuring weight, circumference and density, a quality assessment was done on the mature heads on day 10 after harvest and on day 20 after harvest after storing the heads in a cold store at 4 °C.

  - ***Quality assessments:***

After trimming to obtain TFW, four measured heads from each location were then wrapped in plastic bags and stored at a cold temperature 4°C. On day10 after harvest two heads from each location were taken out from the cold storage and were scored for quality. On day20 after harvest, the remaining two heads of each location were too scored for quality.

Quality scorings were undertaken using standard procedures used by G’s Fresh quality control teams, assessing both internal and external quality including; breakdown, tip burn, mildew, pest damage, viral infection, delamination, ribbiness, rib-cracking, butt-pinking, rib pinking, pinking, density scoring, bolting and misshaping (G’s Fresh Ltd).

2.1.2.3 Results

a) Crop

The three ECa bands had variable fresh weights and dry weights when they were sampled at the early stages of growth (14 days after planting). The fresh weight variation was significant between the locations of the low ECa band and the locations of the high ECa band (Figure 2.16). Similarly, the dry weight differed significantly between the low and the high ECa bands (Figure 2.17). The ECa band with the lowest electric conductivity had the highest means of both plants fresh weight and dry weights. (Figures 2.16 and 2.17).

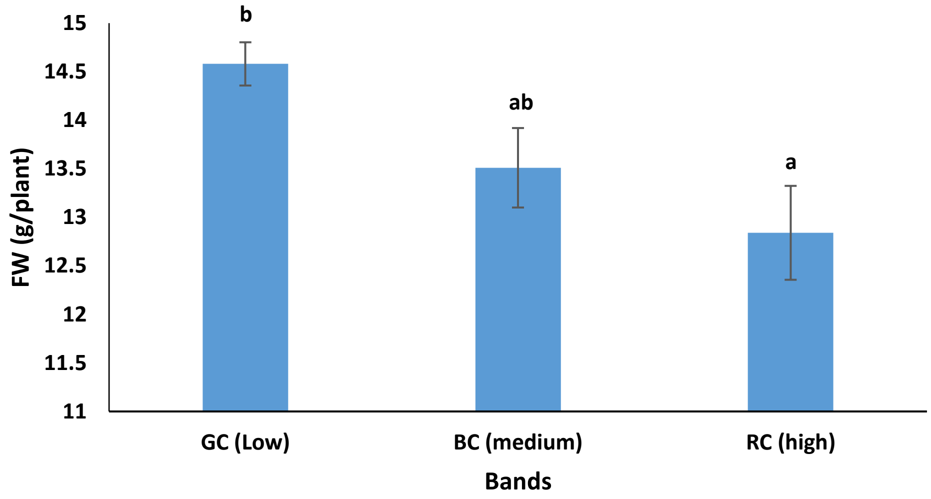


Figure 2.16. Total FW of young plants g / plant on day14 after planting. Error bars show standard error for the location of each band (n=7) as averaged between the samples (n=10). Where lower-case letters differ, values are significantly different (P<.05).

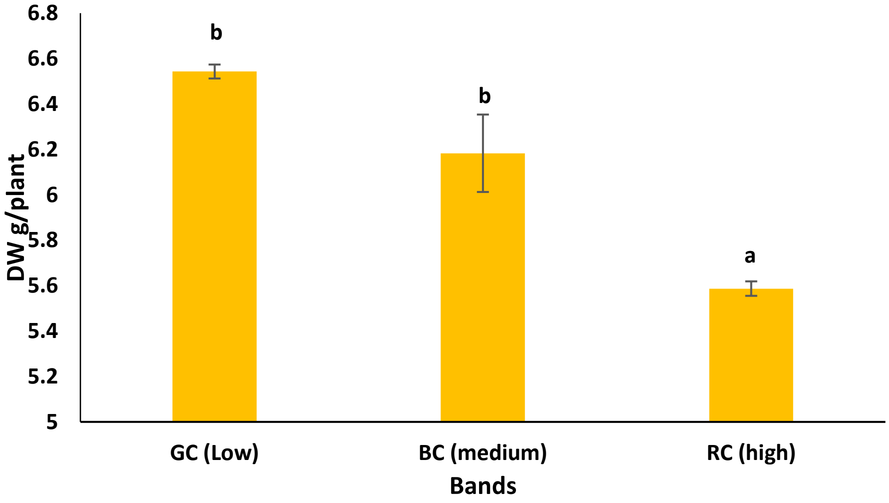


Figure 2.17. Total DW of young plants g/plant on day14 after planting. Error bars show standard error for averages (n=7) as averaged between the samples (n=10 per location). Where lower case letters differ, values are significantly different (P<.05)

However, at mid-growth and at maturity, no significant differences were found in the fresh weights, the dry weights or any of the examined parameters of the three different ECa bands (zones). These results are displayed in Table 2.8.

Table 2.8. Examined crop parameters and the significant difference (S) or non-significant difference (NS) between the bands on each sampling or examining date.

	Day14 after planting	**Day35 after planting**	**Maturity (at harvest)**	**Day10 post-harvest**	**Day20 post-harvest**
FW	0.02	NS	NS	NS	NS
DW	< .001	NS	NS	_	_
Leaf count	NS	_	_	_	_
Circumference	_	_	NS	_	_
Density score	_	_	NS	NS	NS
Quality score	_	_	_	NS	NS

b) Soil

There were no significant differences in pH or organic matter (the averages of organic matter contents were 47.6 %, 41.4 % and 39.9 %, and the mean pH values were 7.3, 7.4 and 7.5 for the three ECa bands low, medium and high respectively) Soil texture analysis and soil type classification using the texture triangle showed only a slight difference in the type of soil with the lowest ECa (Band GC) in comparison with the soil of medium and high ECa (BC and RC) (Table 2.9). Statistical analysis for the soil particles distribution results (the fractions of sand silt and clay) did not show any significant differences between the bands.

Table 2.9 Soil bands, their type according to soil texture triangle and the proportion of clay, sand and silt as percentages as averaged between the samples (n=7).

ECa Band	Type	Sand%	Clay%	Silt%
G (low)	Silty Clay	9.5	39.8	50.8
BC (medium)	Silty Clay Loam	14.1	33.3	52.6
RG (high)	Silty Clay Loam	6.5	36.4	57

Analysis of Variance showed no significant difference between the soil of different bands in terms of contents of soil particle distribution for sand, silt or clay.

2.1.3 Discussion for experiments FT1 and FT2

FT1: Examining soil properties in the zones identified using different soil ECa ranges showed significant differences in most soil properties agreeing, with several earlier studies, where coincidence between variable ECa and variable soil zones across the field has commonly been identified (e.g. Earl *et al*., 2003; James *et al*., 2003 and Taylor *et al*., 2003). The density of soil samples taken and analysed was higher than the density adopted and recommended by James *et al*. (2003), where strong correlation between ECa variability and soil variability at a higher sampling density (4 - 8 samples per hectare) was found. This may support the results of this study where the number of samples was increased to build up a higher density of observations.

ECa and plant growth: Zone A, which fell into the lowest ECa range, had the lowest fresh weight and dry weight at both mid-growth and at harvest. Although, Zone A was not significantly different from Zone C in dry weight at mid growth, it was still considerably lower. Similarly, in terms of the marketable yield, the trimmed-head weights in Zone A were significantly lower than Zone B and C. No significant differences were found between the latter two zones. Although there were no significant differences in terms of trimmed head circumference between any of the zones, the mid-growth rosette diameters were also smaller in Zone A.

This difference in fresh and dry weights between Zone A and Zones B and C indicates reduced or delayed growth in Zone A that continued to harvest. The difference in fresh weight and rosette diameter between Zones B and C that was significant at mid growth, was reduced at harvest, with a similar pattern being observed for the marketable (trimmed) head weight at harvest. This suggests that the difference in the growth of young plants between these two zones was large enough to continue to harvest, although it was less at harvest, and could possibly be due to more overdeveloped rather than underdeveloped young plants. This was explained previously by Kerbiriou *et al*., (2013b) that the variability in size between young plants declines in time particularly for the overdeveloped plants in comparison to normal plants and that overdeveloped transplants do not affect the final yield (Kerbiriou *et al*., 2013b).

The proportion of variation that was recorded at the mid-growth stage and continued to harvest (in particular between Zone A and both of Zones B and C) could suggested a variation in growth and development that starts at early stages of growth and affects the biomass acquired by harvest. This also is supported by Kerbiriou *et al*. (2013b) where it was demonstrated that transplants of smaller size affected growth and development continuously as well as the final yield.

Zone A and Zone B were similar in head density but Zone C was higher. The lack of difference in head density between Zones A and B could mean that soil factors that change between Zones A and B have no effect on head density. Furthermore, all samples showed relatively low-density scores, (the highest density scored was 4 out of 8 and for a limited number of samples (8 / 75). Head density in lettuce is largely attributed to weather conditions (Wein, 1997 and Ryder, 1999) and this parameter could have benefited from a greater number of samples as the difference to be detected is small and the method used to assess density was relatively subjective.

Soil texture and type: Zone A had the lowest percentage of organic matter (39 %), in comparison with 51 % for Zone B and 47 % for Zone C. In terms of classification and soil type, the soil from Zones B and Zone C, Zone A falls at the bottom end of the loamy peat class, Zone C is at the top of this soil class whereas Zone B falls in the peat class (Natural England, 2008).

Determining the soil texture class for the mineral fraction of the soil using the particle size distribution test was performed for the purpose of comparison between the three zones. Using the soil texture triangle (Natural England, 2008) did not show substantial differences in soil type, the same type of soil existed in three zones across the three examined depths, except for minor differences for Zone C where it was silty clay at 0 – 30 cm depth, instead of silty clay loam as in the rest of the zones and depths. However, when comparing the clay content between zones, Zone A had the lowest clay percentage, although significantly lower than Zone C ($P < 0.05$ and 13 % lower), it was not significantly lower than Zone B (4% lower). This difference in clay content can potentially explain both differences in the ECa range and the lettuce fresh weights. De Benedetto *et al*., (2010) found strong correlation between clay content and soil ECa, meanwhile, Stadler *et al.* (2015) found a strong correlation between ECa and soil texture and moisture. This is supported by De Benedetto *et al*., (2010), who showed the importance of clay content in determining soil hydraulic properties and water holding capacity as well as its strong correlation with ECa surveys under uniform soil water conditions. Furthermore, clay particles are known for their large surface area and specific surface area which allow the adsorption of much larger amounts of nutrients in comparison to silt and clay particles (Brady and Weil, 2006).

The difference in yield between Zone A and the other two zones therefore, is suggested to be a result of the difference in texture and soil moisture properties, especially since Zone A did not display a lack of the measured nutrients (Mg, K or P) in comparison with Zones

B and C. This contradicts with Costigan and McBurney (1983), who associated the difference in lettuce growth on two similar sandy loam soils with reduced levels of potassium and phosphorus. Indeed, Zone C, which had the highest fresh weight was the lowest in phosphorus and potassium.

The trimmed head fresh weight (TFW) significantly correlated with the total head fresh weight (FW) and soil magnesium content. FW was correlated with organic matter, magnesium and potassium content. And organic matter was significantly correlated with magnesium and potassium. The similarity in the trend between the whole head fresh weight, trimmed head fresh weight and organic matter therefore, is potentially linked to the effect of Mg and P on the FW and the effect of Mg on the TFW or possibly the hearting process. This suggests that enhanced growth and leaf production could be associated with better soil organic matter in Zones B and C (51 % for Zone B and 47 % for Zone C in comparison with 39 % for Zone A) . And this could also be attributed to a number of reasons from improving the physical quality of the soil (Dexter 2004a) to enhanced rooting intensity and reduced compressibility and machinery damage (Loveland and Webb, 2003). This is also supported by the findings of Arvidsson (1998), which showed that organic matter had more effect on yield and the physical quality of the soil than soil particle size distribution.

It is possible that the difference in growth that was recorded at mid - growth, had been established early on when the plants were young, similarly to the results of Costigan (1983a), where the difference in dry matter was established when the plants were young and subsequently applying fertilizers was not sufficient to improve the soil ability to supply phosphorus and potassium to the plants to increase the yield. Although in this experiment, there was no evidence of a shortage of these elements.

Obtaining soil indexes from nutrient concentrations showed different fertiliser recommendations for the three zones for each of Mg, P and K, which indicates that some areas of the field can receive superfluous or reduced amounts of fertilisers when treated uniformly. The significant difference in clay % suggests that the precision of using soil texture triangle for determining zonal soil type is not adequate for determining the uniformity of a field. De Benedetto *et al*. (2010), suggested that clay content is a more reliable measurement for soil in-field variability.

The trend that was observed between FW and TW at harvest and clay % and OM suggests a possible link to nutrients and moisture holding capacity. Part of the correlation between the whole-head fresh weight with Mg and K could partially be a result of or a reason for the correlation with OM and clay %, as these nutrients are known to be strongly interactive with clay minerals and organic matter, which in turn determine their availability for the plants (Brady and Weil, 2006; Marschner, 2012). Hence, further investigation is proposed that focus more on the available nutrients and the effect of differences in their concentrations and mobility on lettuce variability.

Soil pH values for the three zones ranged between 7.4 for both Zones A and C to 7.5 for Zone B. and no relationship was found between plant growth and pH which conforms with the findings of Costigan, (1986) where no effect of soil pH on lettuce growth rates was found, despite soil pH values as low as 6.

FT2: According to the soil texture triangle classification for the mineral fraction of the soil, the difference in soil type between the three ranges of ECa that were distributed in small scale zones were not substantial. The difference between each particle size component was not significant. The difference in fresh weight and dry weight that was found at mid growth between the three different bands of ECa, which disappeared at later stages of growth could be explained by the growth of the plants where the roots became capable of further exploration of the soil. And in this case the roots have a smaller space of supposedly poor soil conditions to overcome which was mitigated by the soil from the surrounding areas. This suggestion is possibly supported by the findings of Zink and Yamaguchi (1962) findings in that uptake of most nutrients (70 %) in lettuce occurs toward the last 21 days before harvest, correspondingly to a relatively higher growth rate in comparison with earlier stages of growth.

2.1.3.1 Conclusions of the experiments FT1 and FT2:

- ECa scans can be used to identify different soil zones within a field and enable targeted soil sampling. However, they cannot be used as per the results of this experiment for underpinning the underpinning the underlaying causes of this variation in yield or in ECa ranges, as no correlations were found between the latter two properties and the measured soil factors.
- Samples from soil zones that varied in ECa range varied statistically in percentage clay content and in the nutrients magnesium, Mg; potassium, K and phosphorus, P.
- Plant growth varied between the zones midway through growth (35 days after planting) and at harvest.
- Demarcating variable soil-ECa zones at a smaller scale (smaller than 3 m^2) proved inefficient for studying the potential for increasing lettuce crop uniformity through variable management.

2.1.3.2 Limitations of the experiments FT1 and FT2:

A limitation of the experimental design and analysis for this approach was that there was a lack of real replication and as such the potential for pseudo replication. However, the data were treated as preliminary and were used to identify trends of interest for subsequent experiments using different methods. The maximum number of samples was obtained from the three ECa zones and it was not possible to truly replicate the study as when shifting to a different area of the field it would not been possible to find the same ECa values, and therefore the change of bands was done in FT2 as ECa values and scale of variation changed with the field area.

The head density determination method was relatively subjective, and the alternative for this method would have been to quantify the density in a mathematical method using the circumference or the geometry of the trimmed head fresh weight method, similar to Jenni and Bourgeois (2008). However, in these two experiments (FT1 and FT2) only one circumference was measured for lettuce heads, and considering that lettuce heads are not spherical in addition to the occurrence of the head misshaping phenomenon in Iceberg lettuce heads, where the curved leaves of the enclosed head grow asymmetrically to one side of the stem more than the other, creating irregularly shaped heads, using one circumference to quantify head density would have possibly increased the error in the density assessments. Other options could have also have been measuring water displacement by immersing lettuce head in water, however, that also have been very time consuming and very unlikely to be practical for farmers.

2.2 Experiment FT3 and FT4: The effect of variable soil properties on lettuce yield

2.2.1 Introduction

The development of computerised geographical information systems (GIS) and field mapping tools with electrical conductivity (ECa) has made in-field soil variation both identifiable and quantifiable, allowing the modification of agricultural inputs based on zonal distribution of soil physicochemical properties (Corwin *et al*., 2003).

The experiment FT1 identified variable zones in the field Redmere P36 in terms of soil and yield properties within the field when targeted sampling was followed using ECa scans. However, despite the high density of soil samples in the centres of the targeted zones of low, medium and high ECa, the transitional or bordering areas between these zones or the areas that had mixed ECa ranges, were not included in the sampling or investigation of FT1 and FT2. Therefore, further investigation was needed inthese areas.

Grid soil sampling with variable sampling densities has been used to examine the relationship between ECa scans and soil and yield properties (Earl *et al*., 2003; James *et al.,* 2003; Grisso *et al*., 2009; Zhu *et al*., 2010 and Doolittle and Brevik, 2014). James *et al.,* (2003) used irregular grid sampling densities from 1 to 8 samples per hectare, finding better correlation between ECa maps and the most intensive sampling density. Grid sampling, when used in commercial settings, is commonly spaced at 100 m X 100 m grids (Earl *et al*., 2003). Taylor *et al.* (2003) conducted a soil survey following a more intensive grid (25 m X 25 m) however, this study did not look at yield variation in correspondence to soil variability.

The yield of cereal crops has been successfully mapped using mass flow sensors (Stafford *et al*., 1996; Taylor *et al.*, 2003). Most cereal crop yield maps correspond to soil ECa maps and soil series, particularly in drier years (Earl *et al.,* 2003; Stadler *et al*., 2015) where differences between soil types are more apparent due to the difference in soil moisture properties that become more important in dry conditions. This enables the use of soil maps and soil ECa maps to predict yield variability patterns across the field. However, for lettuce crops, yield mapping has not been developed due to the manual harvesting of the crop. Panagopoulos *et al.,* (2006) localized zonal soil problems (mostly moisture related) and recommended variable management or amendment decisions to improve lettuce production in those zones in order to optimise the yield across the field.

Exclusive use of either crop yield maps or ECa maps to inform in-field variable management decision for a crop is invalid as yield maps, although able to provide an indication of soil condition and properties, do not provide sufficient information on these properties and of the interactions of various soil factors in that field. Soil maps alone, however, are insufficient for predicting yield responses to these soil properties (Corwin *et al*., 2003)

Considering the complex and inconsistent relationship between yield, ECa and soil properties, as well as the complexity that governs interpreting their maps (Corwin *et al.,* 2003; Corwin and Lesch, 2003) further systematic collection of data was needed to gather more information about the lettuce crop and soil properties. Variable management decisions for field-grown Iceberg using soil property ECa maps requires identification of sources and scales of variation and this could not be done without increasing the spatial and the temporal scale of the sampling that was done in FT1 and FT2 to cover transitional values between zones and examine the seasonal variability.

In experiments FT3 and FT4, soil physicochemical properties that can affect lettuce growth were investigated and the potential for using maps of key soil physical properties and soil ECa scans to predict lettuce yield variation in an attempt to improve harvest efficiency by providing targeted solutions in spatial and temporal aspects at a field scale was explored.

Since the annual variability of the yield is mainly influenced by current year conditions represented by all the factors that determine the production for that year and resulting in total inter-year yield offset (Blackmore *et al*., 2003), this study will not discuss the inter-year offset (the annual variation). Instead, it will examine seasonal variability; the spatial distribution of lettuce yield from one season to another within the same year (two successive croppings in the same field). This would enable taking into consideration the interaction between constant and changing edaphic factors which can be influenced by weather conditions.

The aims:

(i) Examine the spatial and seasonal variability of the lettuce yield over the studied area.
(ii) Identify the key underlying soil properties that influence lettuce yield distribution.
(iii) Investigate the possibility of using maps of other soil properties, in addition to soil ECa maps, to inform precision management decision for lettuce crops.

Null hypothesis:

Lettuce yield does not vary spatially across the studied field.

Lettuce yield does not vary seasonally in the studied field.

Lettuce yield is not determined by a limited number of soil edaphic factors.

2.2.2 Materials and methods for the experiments FT3 and FT4

a) Site specifications

The experiment was established in field P57, G’s Farm, Littleport, Cambridgeshire, georeferenced as (52° 27.152'N, 0° 24.184'E). The field had a working area of 8.64ha (Figure 2.18).

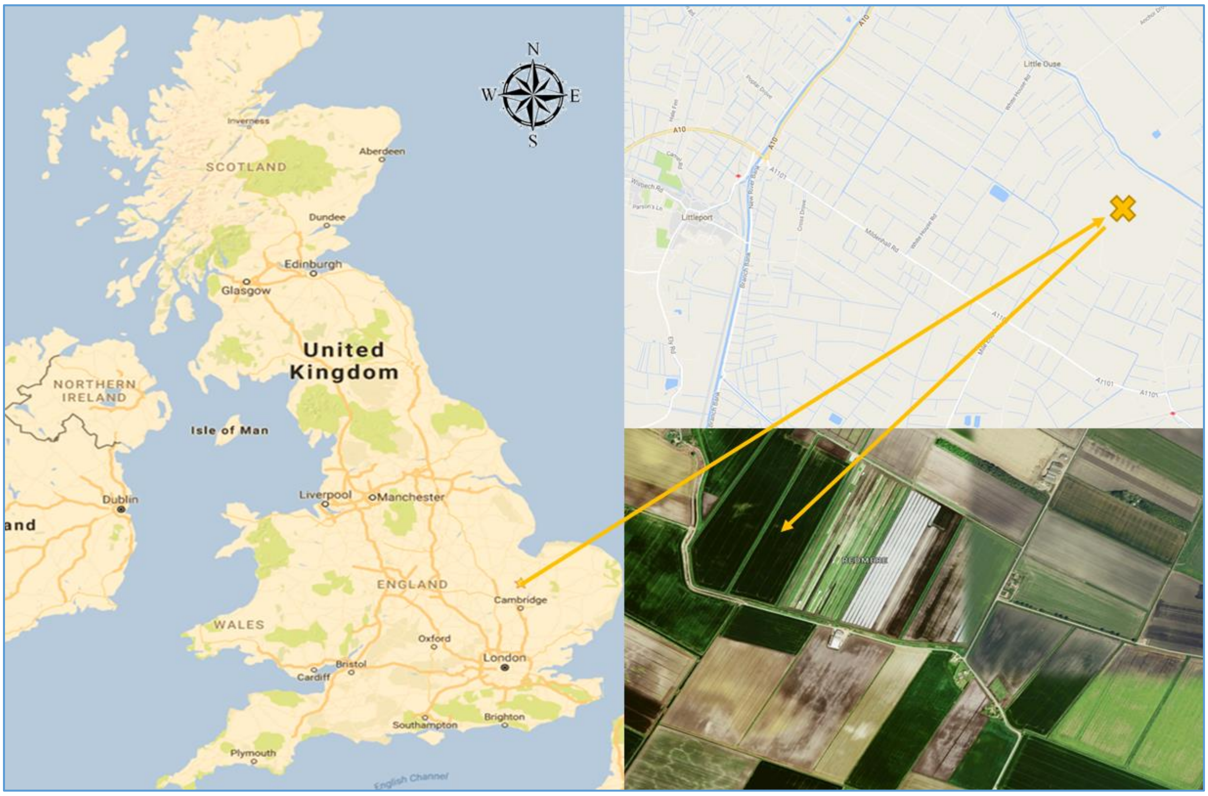


Figure 2.18. The experiment site and location on G’s Farm (Redmere) in Littleport, Cambridgeshire, UK.

The soil was classified as loamy and sandy with a peaty surface, naturally wet with high groundwater where fields drain locally to shallow marginal ditches. This makes water resource in the area vulnerable to pollution from fertiliser and pesticides applied to the land (National Soil Map and Soilscapes Dataset, 2015). The study area received a total rainfall of 44.6 mm for FT3 and 71.6 mm for FT4 (Table 2.10) for the crop growing cycle from planting to harvest (around 57 days for FT3 and 44 days for FT4). Average air temperature was 11.5°C for FT3 and 14.1°C, as recorded by Redmere Weather Station, Cambridgeshire, which is located within 3 miles from the studied field.

Table 2.10 Weather data for both crops (FT3 and FT4) as recorded by Redmere weather station, G’s, Cambridgeshire, UK. For the period from 13 April 2015 to 8 June 2015 for FT3 and from 29 July 2015 to 10 September 2015 for FT4.

	Accumulated rainfall [mm]	Average daily temperature [°C]	Maximum temperature [°C]	Minimum temperature [°C]	Relative humidity [%]
FT3	44.6	11.5	17	4.6	74
FT4	71.6	14.1	21	9.6	84

b) Crop production

The field was used to grow two commercial crops of iceberg lettuce (*Lactuca sativa* cv Challenger). FT3 lettuce were transplanted on 13 April 2015 and harvested 8 June 2015 (56 days). FT4 lettuce were transplanted on 29 July 2015 and harvested on 10 September 2015 (43 days). Lettuce transplants were planted commercially using a mechanical transplanter (Regero, France). Plant spacing was 30 x 30 cm for FT3 (early crop, slower growth due to lower weather temperature and solar radiation levels) and 30 x 35 cm for FT4 (summer crop, faster growth due to greater temperatures and solar radiation levels). The crops were grown following standard practice to control weeds, pests and diseases. The amounts of fertiliser applied are shown in Table 2.11. The crops were irrigated using an overhead irrigation system and according to the standard application rates and soil moisture deficits.

Table 2.11. The fertilisers applied for Redmere P57 for FT3 and FT4 crops in 2015

Crop/ experiment	Period	N (kg / ha)	P_2O_5 (kg / ha)	K_2O (kg / ha)
FT3	4/2015 to 6/2015	126.54	96.72	95.43
FT4	7/2015 to 9/2015	80.6	80.6	0

c) *Sampling locations*

The same locations were sampled for FT3 and for FT4. Samples were taken in a regular 20 m x 25 m grid, laid down in the central part of the field to avoid boundary effects (Figure 2.19) and the 63 locations were positioned using the Geo 7X handheld GPS unit (Trimble, UK) with DGNSS accuracy < 1m.

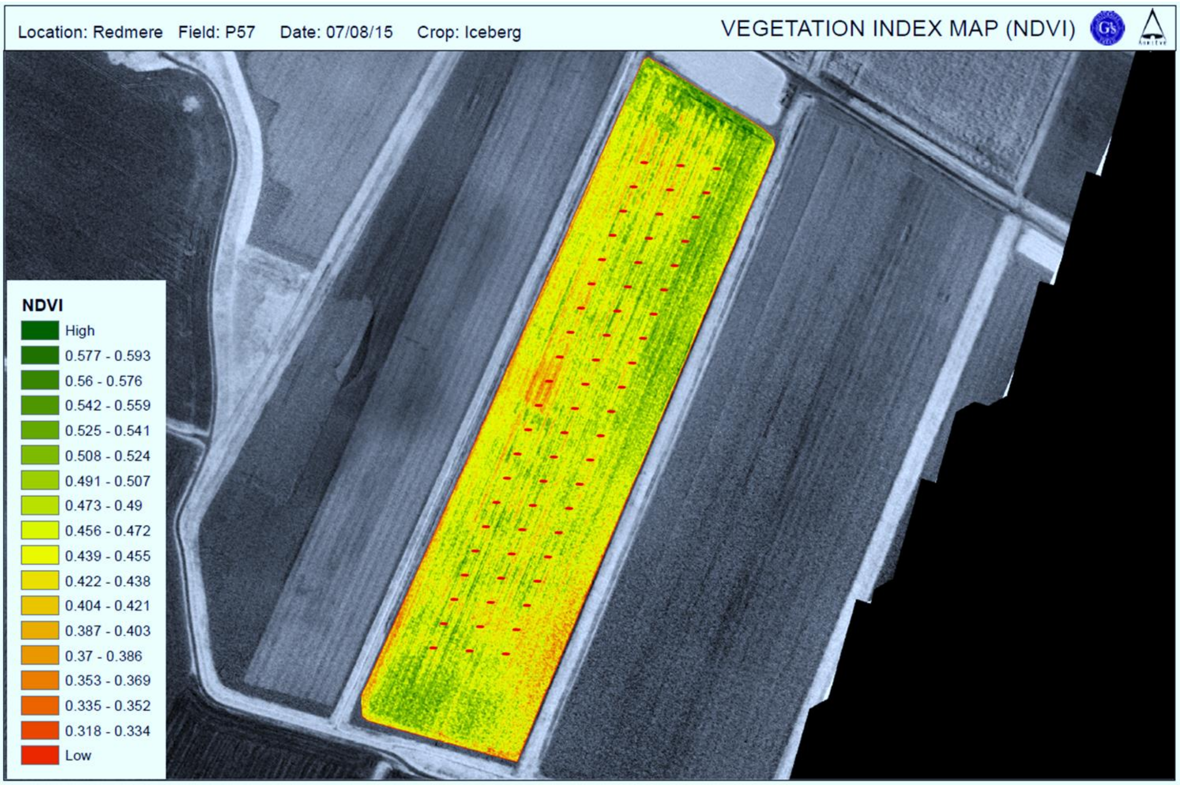


Figure 2.19: Normalised difference Vegetation index map of the field Redmere P57. The red dots in the central part of the field represent the sampling grid.
(Source: G's Grower's Ltd)

d) *Plant sampling*

Plants were sampled for FT3 and FT4 two to three days before commercial harvest. Five heads were cut at each location in FT3 and 4 heads per location in FT4 by cutting the plant at the soil level with a sharp harvest knife. The total fresh weight was recorded *in situ* for FT3 and in the laboratory at HAU for FT4 using a digital balance (KERN FKB 16K0.1, KERN and Sohn, GmbH, Balingen, Germany). The outer leaves were removed following commercial practice and the trimmed heads were weighed. The dry weight of the trimmed heads was measured after drying the heads in forced air ovens at 80 °C for a minimum of 96 hours after cutting the heads in half for more even drying.

e) *Soil data collection*

Soil samples were taken from each sampling location at two depths 0-30cm and 30-60cm using soil gouge augers (EijkelKamp, Netherlands). The lengths of the augers were 30 cm and 60 cm of diameters 40 mm and 30 mm, respectively. The top 10 cm of soil was removed and discarded, and a bulk density sample was taken using a bulk density cylinder (10 cm radius and 11 cm depth) at 10 - 20 cm of soil depth. All samples were placed in separate, labelled and sealed plastic bags. The bulk density samples were weighed in the laboratory and dried at 105 C° for 24 h (Rowell, 1994) then reweighed.

Soil samples from depths 0 – 30 cm and 30 – 60 cm were transferred into sealed plastic bags and taken to the laboratory at HAU and air dried for 2-3 weeks. The samples were milled using a pestle and mortar and screened over a 2.0 mm sieve to remove stones. Subsamples of approximately 20 g were taken from each of the 63 samples of each depth for analysis of organic matter and soil texture. Soil nutrient analysis (total N, P and K) was carried out at NRM Laboratories, Berkshire.

Organic matter was quantified by the loss on ignition method after heating the oven dried soil at 500 °C for 6 hours (Schulte and Hopkins, 1996). Texture was analysed after digesting the soil organic matter using hydrogen peroxide by dosing the measured soil sample with the hydrogen peroxide inside Petry dishes for 7 days or until the reaction stops. Particle size distribution was determined for the mineral fraction of the soil using the Laser Diffraction method with a Mastersizer2000 (Malvern Instruments Ltd Worcestershire, UK) with a measurement range between 0.5 µm to 3000 µm (Eshel *et al*., 2004). at the Instrumental analysis laboratory at the University of Birmingham

f) Soil electric conductivity scans

Field P57 was scanned commercially for soil ECa on 11/03/2014, using a Veris E3100 scanner, whilst it was in wheat stubble. The scanning bout width was 10-12 m and was operated at an average of 24 m spacing between bouts and was carried out by Fresh Produce Consultancy Ltd, Ely, Cambridgeshire. The equipment provided scans at two depths: 0 – 30 cm and 30 – 60 cm. The ECa scanner used a Differential Global Positioning System (DGPS) so geo-referencing accuracy is suggested to be within 30 cm (Esri, 2014a). The raw scanned data (including the GPS coordinates) were processed and then plotted on Google Earth, using the Google Earth software (Google Earth Pro. 7.3.0.3832. 2017) to locate the ECa values on the field site.

g) *Data mapping*

All soil and plant data were mapped in the Geostatistical Analyst tool in ArcGIS (Esri, 10.5.1) using the inverse distant weighting method and classifying the data into 10 classes following the same range of colours for all the maps (Bing *et al*., 2006; Krygier and Wood., 2005; Jankowski., 1995). The mapping was done following standard methods for map making in GIS (Field, 2009; Krygier and Wood., 2005). Ten classes enable the map readers to see distinct boundaries of the mapped traits (Field, 2009). The classification was done using the geometric intervals method in the geostatistical analyst in ArcGIS, due to the suitability of this method for visualising data, in particular those that are not normally distributed or are heavily skewed (Esri, 2010).

Historical wheat yield data for 2014 for P57 was provided by the grower. The yield was collected from the Claas combine harvester at harvest. The wheat yield's raw data values for the locations used for sampling within the lettuce experiments were estimated using Google Earth software by averaging the values of the nearest wheat yield data points to each of the 63 sampling locations. The distance to the surrounding values was measured using the ruler tool in Google Earth software and the nearest three values to the sampling locations were averaged, the average distance aimed for was within 3 m from the sampling location.

H) Profile Pits

Redmere P57 was further examined by excavating four profile pits to investigate soil structure up to 100 cm depth. Two pits were excavated in a two of the high yielding zones and two in a two of the low yielding zone. Soil profile in the pits was examined and information were recorded: soil horizons, colours and depths were recorded (Rowell, 1995). Horizons were identified and measured in terms of depth using a ruler and penetration resistance was measured for each horizon using a pocket hand held penetrometer where four readings were taken per horizon and then averaged.

2.2.2.1 Statistical Analysis

Multiple plots were created to examine the characteristics of the data. The data were checked for normality by computing and plotting histograms and examining them for outliers as well as by calculating the skewness (Webster & Oliver, 2007). The histograms of the data were checked for normality. The coefficient of variation for the data per location was checked on ArcGIS software (ArcMap) (ESRI, 2011) for abnormalities or outliers.

Two sample T-test was used to examine the difference between the yields of FT3 and FT4 as well as the difference between the measured soil properties at two depths. Correlation analysis was used to examine the relationship of the yields of both trials with the measured soil parameters.

A descriptive statistical analysis of the data was carried out for soil physicochemical properties that were measured for the top 0 - 30 cm and 30 - 60 cm and a correlation matrix that utilised standard Pearson correlation coefficients was produced for the measured soil properties.

Modelling response to nutrients:

Multilinear regression with feature selection was used to avoid collinearity / multicollinearity i.e. the existence of a highly correlated pair or more than two variables (James *et al.*, 2013). A predictive model was attempted by fitting all models with one predictor (which can also be an interaction) then determining the best model through adding one predictor at a time until the accuracy started to decrease following adding any further predictors. A cross validation was carried out to assess accuracy by excluding 20% of the data points (test set) and running the model using the remaining 80%. The resulting model was tested by using the excluded 20 % of the data in an automated procedure that was repeated 500 times, each time on a different selection of the data (James *et al.*, 2013).

The analysis included all the variables against trimmed fresh weight for FT3 and FT4. Thereafter, the model was used to calculate the predicted change in the yield change when increasing one of the model variables while keeping the other variables constant. Thereafter, locations of low trimmed fresh weight were studied by selecting randomly one of the low yielding locations in the field and using the model to calculate the yield change for that location.

Only the trimmed head weights were modelled after it was shown in FT1 and FT2 that it strongly correlated with the total fresh weights and because the trimmed head weights (the marketable yield) is more relevant to growers.

2.2.2.2 Results

Checking for outliers

The histograms for trimmed head weights from FT3 were slightly asymmetric and did not show a clear normal distribution (Figure 2.20). However, the calculated skewness was < 0.5 allowing the assumption of normality (Webster & Oliver., 2007). The data ranged from 314 g to 716 g per head with an average of 531 g / head.

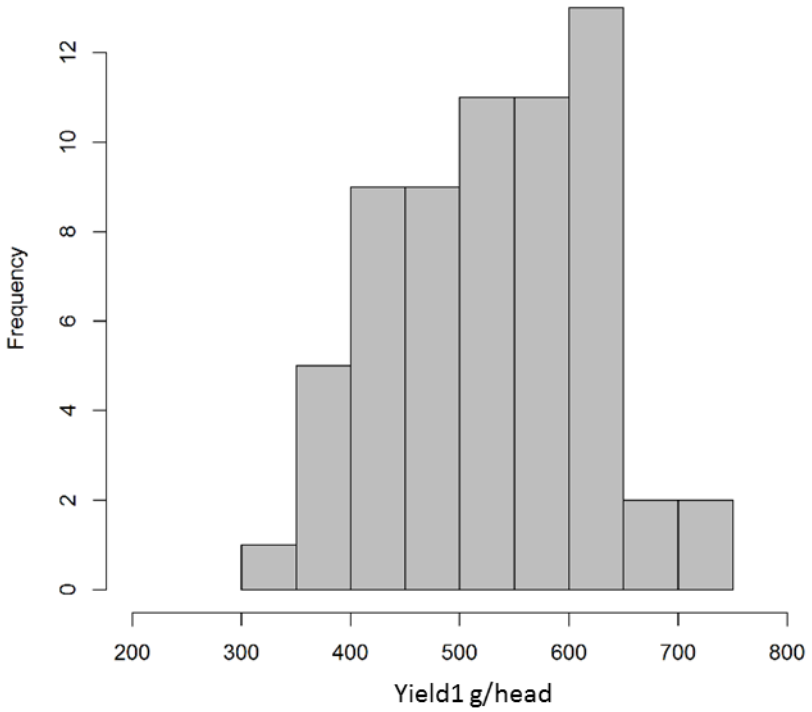


Figure 2.20. Frequency distribution of trimmed head fresh weight, FT3.

The trimmed fresh weight for FT4 was visually symmetrical suggesting a normal distribution of data (Figure 2.21).

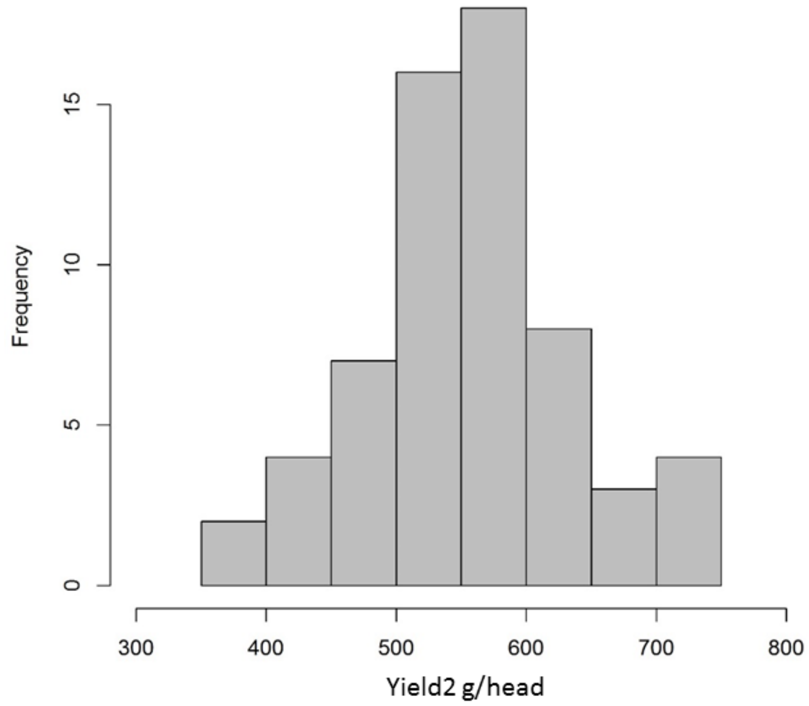


Figure 2.21. Frequency distribution of trimmed head fresh weight, FT4.

The lettuce data for each location were generated from five heads in FT3 and four heads for FT4. Since the FT3 yield data were asymmetric, the variability amongst the five individual heads that generated the average weight for each location was examined, in order to establish the degree of variability amongst the adjacent heads per location in FT3. This was done through calculating the coefficient of variations (CV) for each location then plotting the histograms of the CVs to check their normality (Figure 2.22). The CV histograms showed that all the CV values were below 20 % indicating normal variability amongst adjacent heads of the same location, with two potential outliers where the CV values were above 20% (locations 23 and 34).

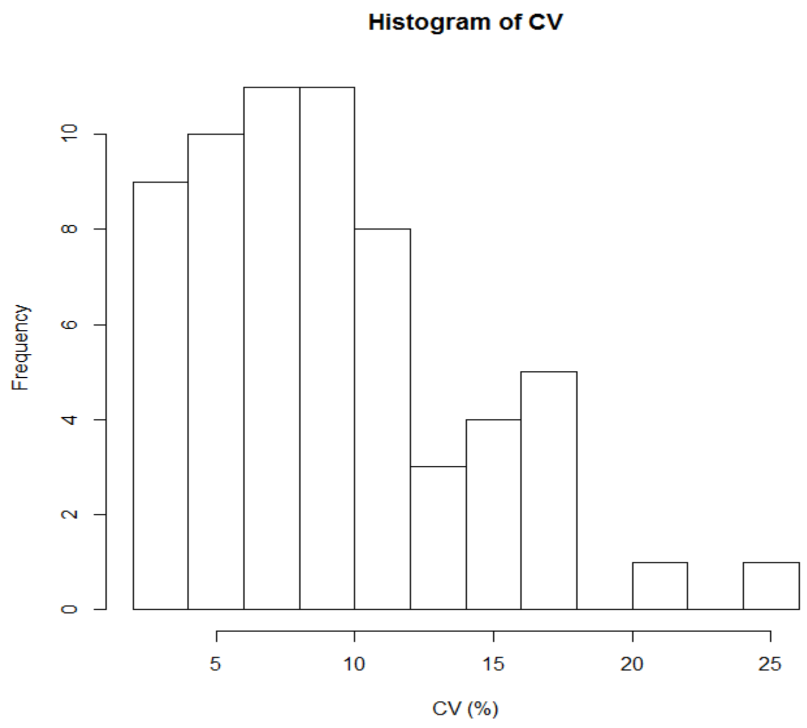


Figure 2.22. Frequency distribution of coefficient of variation for trimmed fresh weight per location (n=5) in FT3.

The individual values of trimmed head fresh weights for locations 23 and 34 are shown in Table 2.12. Head 1 from location 23 and Head 2 from location 34 (indicated with asterisks) were both markedly lower than the average at each location but within the harvestable weight range of a commercial crop (Rob Parker pers. Comm). These two heads were therefore not eliminated as outliers and were kept within the dataset and considered a correct representation of the natural variation in a commercial lettuce crop.

Table 2.12. Coefficient of variation (CV %) for trimmed head fresh weight and individual head measurements at location 23 and 34 in FT3. *potential outliers

CV%	**Head1**	**Head2**	**Head3**	**Head4**	**Head5**
20.90%	325*	542	565	401	577
24.15%	508	266*	620	515	507

a) Lettuce Yield variation and the variability patterns.

There was no significant difference between the trimmed head fresh weights in FT3 and the trimmed head fresh weights in FT4. The two yields were moderately well and significantly correlated (r = 0.5, P < 0.05,) (Figure 2.23). The r^2 however showed that only 24 % of the head weight of FT4 could be related to the head weight at FT3. Average trimmed fresh weight yield was 533 g / head for FT3 and 559 g / head for FT4.

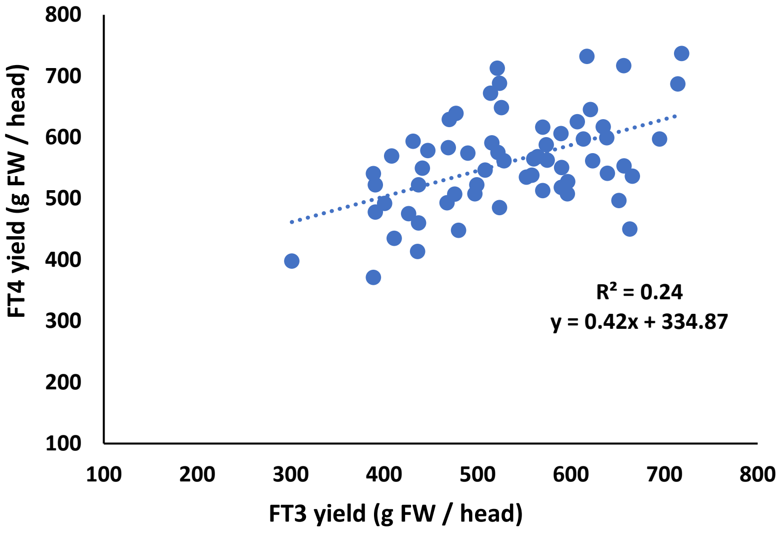


Figure 2.23. The correlation and regression between fresh weight yield of Harvest 1 and Harvest 2 (P<0.001) for n=62 averaged between five heads per location (when harvesting FT4 one of the 63 locations was missing (not planted) therefore its value from FT3 was eliminated).

When mapping both yields the maps showed similar spatial patterns of variability (Figure 2.24). There was an overall similar pattern of yield from north to south and from east to west in both maps.

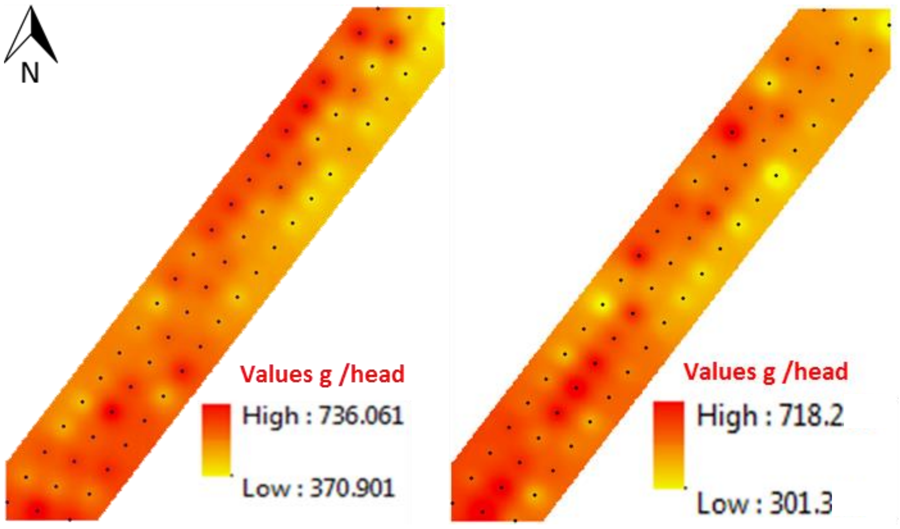


Figure 2.24. Yield of trimmed heads g of fresh weight /head, FT3 yield (left) and FT4 yield (right) mapped using ArcGIS and classified into 10 classes (yield increments between classes were 36.7 g.

There was no significant correlation between wheat yield and lettuce yield for the same sampling locations (r =0.07). The historic wheat yield map for the same field corresponded with the lettuce yield (FT3) trend at the N - S orientation but not at the W - E orientation in the Northern half of the field (Figure 2.25).

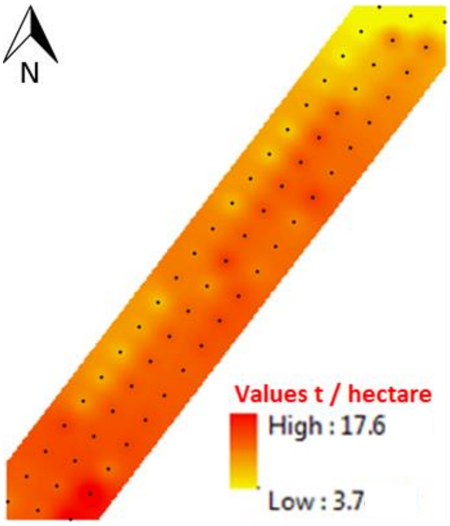


Figure 2.25. Historic wheat yield (t/ha) estimated for the sampling locations using Google Earth, as obtained from the historic data of the whole field, and mapped using ArcGIS, classified into 10 classes.

b) Soil physicochemical Properties

The descriptive statistical data for soil physicochemical properties that were measured for the top 0 - 30 cm and 30 - 60 cm were calculated and presented in Table 2.13. A correlation matrix with standard Pearson correlation coefficients was calculated for the measured soil properties and presented in Table 2.14.

Table 2.13. Means and range statistics of measured soil physicochemical properties for P57.

Soil property*	No. of samples	Mean	Minimum	Maximum	Range	Standard deviation	Standard Error	Coefficient of variation
M%	63	48.0	33.2	61.0	27.7	6.75	0.9	14.07
Pb	63	0.2	0.1	0.3	0.2	0.04	0.00	25.2
R_{soil}	63	0.9	0.4	1.7	1.3	0.28	0.04	30.7
Depth 0-30 cm								
K_{0-30}	63	1702.9	785.0	2926.0	2141.0	575.25	72.5	33.8
N_{0-30}	63	1.3	0.8	2.2	1.5	0.41	0.1	30.8
P_{0-30}	63	1263.7	588.0	1747.0	1159.0	282.42	35.6	22.4
OM_{0-30}	63	35.3	20.8	53.2	32.3	9.88	1.2	28.0
Clay %	63	7.7	2.8	14.8	12.0	2.63	0.3	34.4
Silt %	63	48.4	26.2	84.6	58.4	13.10	1.7	27.1
Sand %	63	43.7	0.4	70.2	69.8	15.53	2.0	35.5
S-EC	63	33.9	8.4	56.4	47.9	13.43	1.7	39.6
Depth 30-60cm								
K_{30-60}	63	2385.2	440.0	5090.0	4650.0	940.88	118.5	39.5
N_{30-60}	63	0.7	0.2	1.5	1.3	0.35	0.04	50.5
P_{30-60}	63	1335.0	358.0	4237.0	3879.0	810.01	102.05	60.7
OM_{30-60}	63	19.5	6.0	38.7	32.7	8.13	1.02	41.7
D-EC	63	33.6	7.8	55.3	47.5	13.48	1.7	40.1

*M%, percentage of soil moisture content; Pb; dry bulk density of the soil g / cm^3, $R_{soil,}$ soil penetration resistance MPa. S-EC; shallow ECa *mS / cm*, D-EC; deep ECa *mS / cm*. Total P and total K reported as mg / kg and total N was reported as % of weight / weight of the dry basis.

Table 2.14. Correlation matrix for FT3 and the measured soil properties for P57

	FT3 yield	Silt	Sand	Clay	TDR	S_EC	R_{soil}	P2	P1	OM2	OM1	N2	N1	K2	K1	D_EC	Bd
Bd	-0.35*	-0.47**	0.47**	-0.41*	-0.4*	-0.33*	0.0034	0.213	-0.187	-0.65**	-0.83**	-0.49**	-0.8**	-0.38*	-0.2	-0.55**	-
D_EC	0.11	0.46**	-0.46**	0.44**	0.4*	0.62**	0.21	-0.34*	-0.08	0.5**	0.57**	0.39*	0.56**	0.49**	0.57**	-	
K1	0.10	0.34*	-0.33*	0.22	0.44*	0.4*	0.15	-0.17	0.57*	0.18	0.22	0.07	0.16	0.39*	-		
K2	0.29*	0.29*	-0.3*	0.33*	0.35*	0.35*	0.11	0.11	0.07	0.17	0.3*	-0.055	0.32*	-			
N1	0.23	0.62**	-0.62**	0.59**	0.41*	0.31*	0.008	-0.3*	0.19	0.71**	0.96**	0.57**	-				
N2	0.25	0.18	-0.18	0.15	0.28*	0.17	0.21	-0.11	-0.006	0.91*	0.54*	-					
OM1	0.23	0.59**	-0.59**	0.55**	0.44**	0.31*	-0.02	-0.31*	0.25	0.69**	-						
OM2	0.29*	0.34*	-0.34*	0.29*	0.37*	0.22	0.08	-0.10	0.1	-							
P1	0.23	0.16	-0.14	0.05	0.26*	-0.08	-0.09	-0.01	-								
P2	0.17	-0.3*	0.3	-0.29	-0.18	-0.27*	-0.003	-									
R_{soil}	0.09	0.08	-0.08	0.05	0.08	0.22	-										
S_EC	0.18	0.23	-0.23	0.22	0.05	-											
TDR	-0.06	0.41*	-0.39*	0.29*	-												
clay	-0.16	0.89**	-0.92*	-													
Sand	0.19	-1	-														
Silt	-0.19	-															
FT3 yield	-																

Bd is the bulk density of the soil in g / cm^3, $R_{soil;}$ soil penetration resistance MPa. S-EC; shallow ECa mS / cm, D-EC; deep ECa mS / cm. Total P and total K reported as mg / kg and total N was reported as % of weight / weight of the dry basis. (1) and (2) indicate topsoil and subsoil. * P<0.05. ** P<0.001

Soil electric conductivity

The ECa values of the shallow scan (0 – 30 cm) correlated moderately with the ECa values of the deep scan (30 – 60 cm) for the sampling locations (r = 0.6, P < 0.001) (Figure 2.26) and there was no significant difference overall between the two depths. The regression equation showed that 38 % of the variation in deep ECa could be explained by the variation in the shallow EC. Soil ECa however, did not correlate at either depth with the yields. Deep Soil ECa however, showed some correlation with organic matter, total nitrogen and potassium at both depths, bulk density as well as with sand and silt content. Shallow ECa showed some weak correlation with potassium at both depths as well as with organic matter at the top depth of the soil.

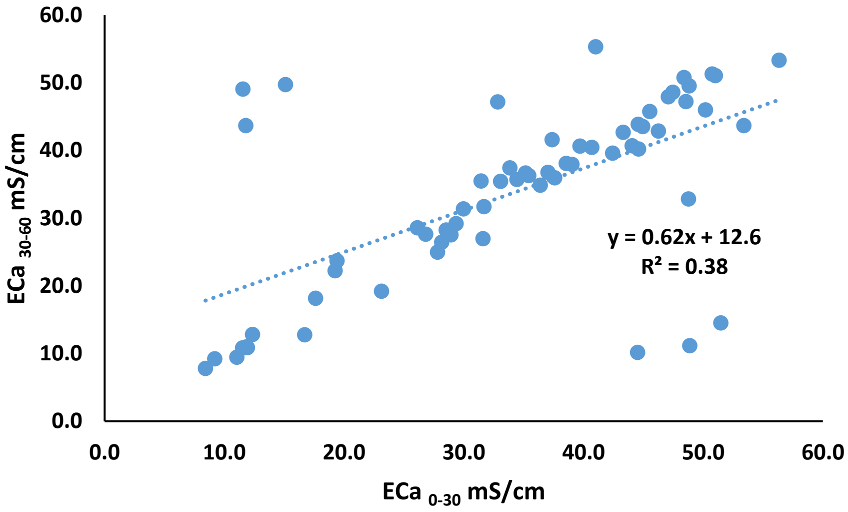


Figure 2.26. The correlation and regression between the shallow ECa values (0 – 30 cm) and the deep ECa values (30 – 60 cm) of the soil (P < .001) n = 63, averaged between the 3 - 4 nearest points per location (georeferenced and estimated using Google Earth.

The two layers of ECa maps showed similar patterns for both the shallow and the deep EC, with markedly lower ECa values around the centre of the field (Figure 2.27).

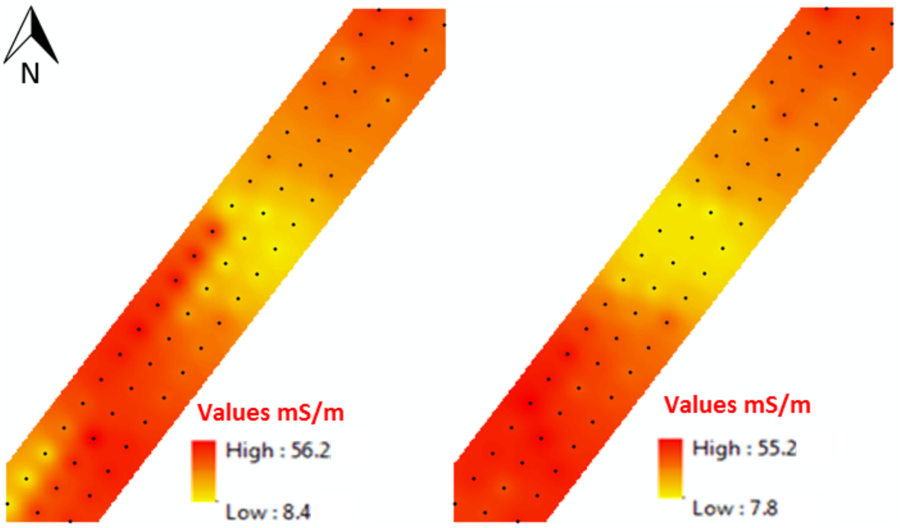


Figure 2.27. The shallow ECa (covering 0 – 30 cm) - left and the deep ECa (covering 30 – 60 cm) - right depth of the soil mS / cm for n = 63 averaged amongst the 3 to 4 nearest points per location, estimated using Google Earth from the raw scanning data as georeferenced and measured over the whole field P 57.

Organic matter

The soil organic matter content in the top 30 cm was significantly greater (35.3%) than that at 30-60 cm depth (19.5%) (Figure 2.28). However, the two were well correlated, r = 0.69, and the coefficient of determination, R^2, showed that 48 % of the variation in OM in the 30 – 60 cm horizon could be predicted from the values in the top 0 - 30 cm horizon as the relationship described as $y = 0.57x - 0.66$; $R^2 = 0.48$, $r = 0.7$, $P < 0.001$) (Figure 2.29).

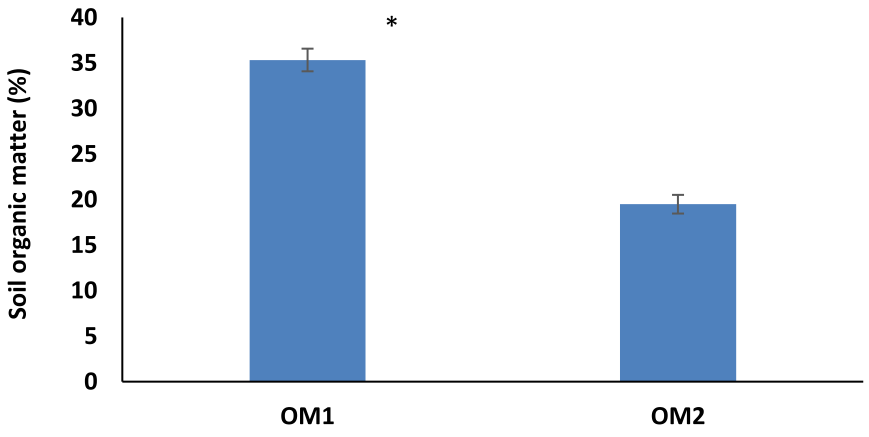


Figure 2.28. The difference in organic matter levels between the depths 0-30 cm (OM1) and 30-60cm (OM2) of the soil.

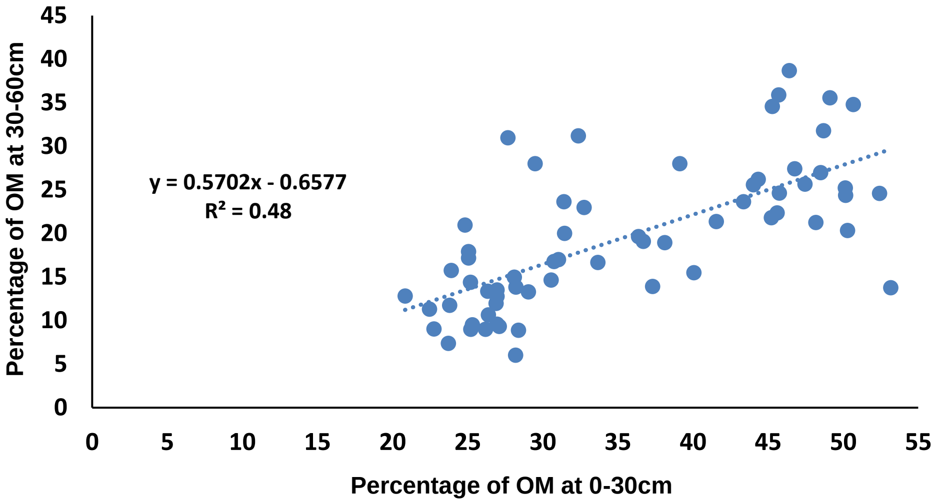


Figure 2.29. The correlation between organic matter (OM) at 0-30 cm and 30-60 cm of the soil ($P<.001$, $R^2 = 0.48$, for $n=63$).

The organic matter was distributed in a relatively similar pattern at both layers of soil where the southern part of the field had the greatest amount of organic matter at both depths (Figure 2.30).

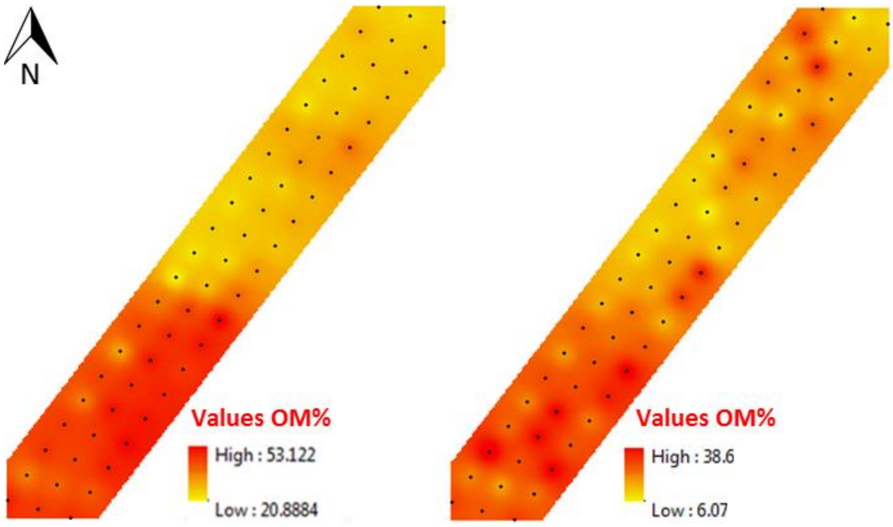


Figure 2.30. Soil organic matter content as a percentage map at 0-30cm depth (left) and 30-60cm depth (right).

Soil ECa and OM were both notably greater in the southern part of the field in comparison to the northern part of the field. This general trend was also found (to some extent) in moisture (Figures 2.31), clay (Figure 2.32) and silt (Figure 2.33). However, no useful correlation was found amongst these factors except for the correlations amongst texture mineral components. The moisture map that was created using the TDR data (Figure 2.31 - left) corresponded more to the observations in the field (during the on-site sampling process, water logging conditions were observed in the same locations correspondingly to the locations with higher moisture content value as recorded by the TDR). Some of the locations that showed the high moisture content on the TDR map but not on the volumetric water content map were noted to have moist and sometimes water-logged areas nearby during sampling. Therefore, the TDR dataset was chosen to be used later for modelling and for further analysis.

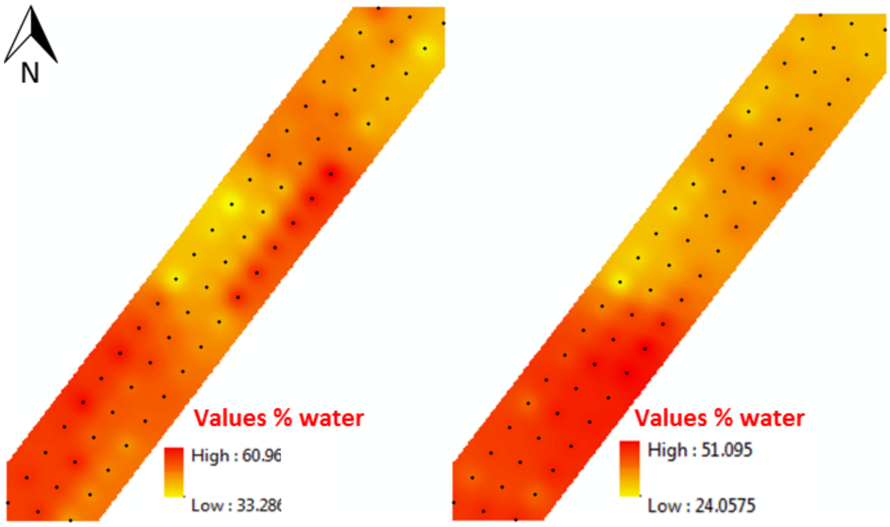


Figure 2.31. Soil moisture map at 0 – 20 cm, data collected using TDR field scout (left) and using the volumetric water content (right).

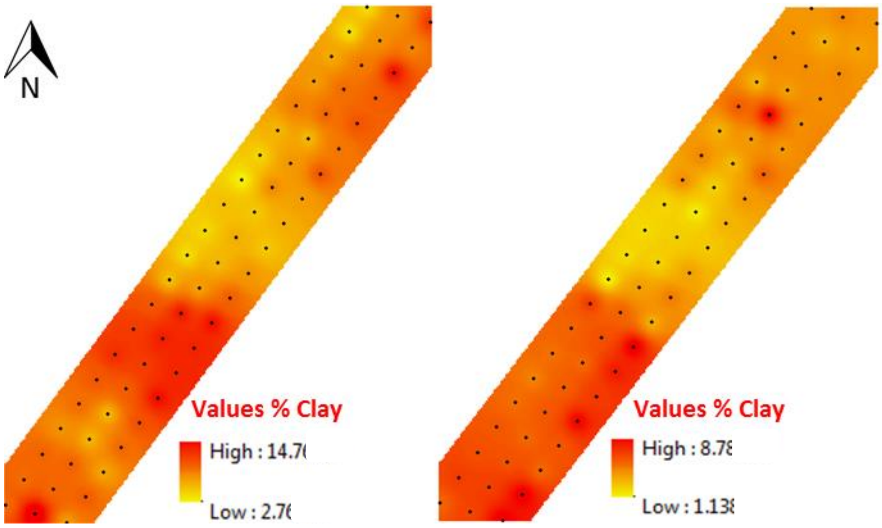


Figure 2.32. Soil clay content as a percentage of the mineral component of the soil, mapped at 0 – 30 cm depth (left) and 30 – 60 cm depth (right).

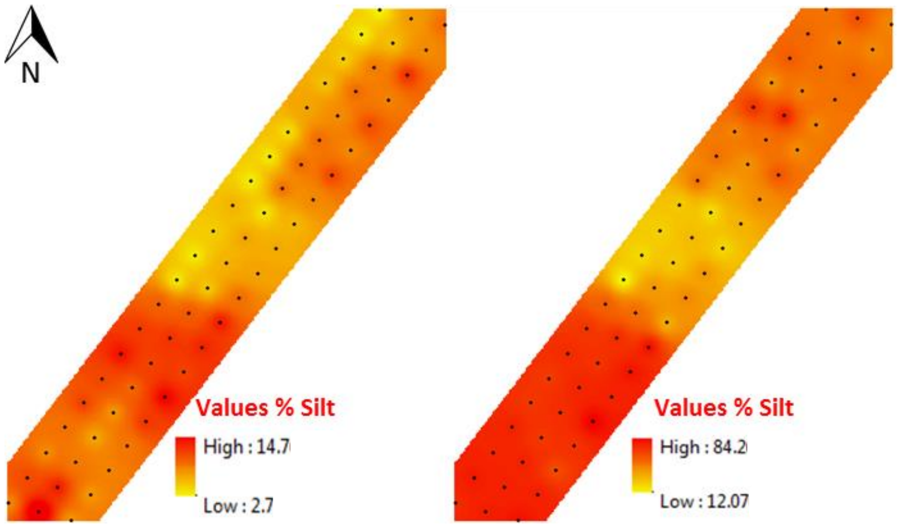


Figure 2.33. Soil Silt content as a percentage of the mineral component of the soil, mapped at 0 – 30 cm depth (left) and 30 – 60 cm depth (right).

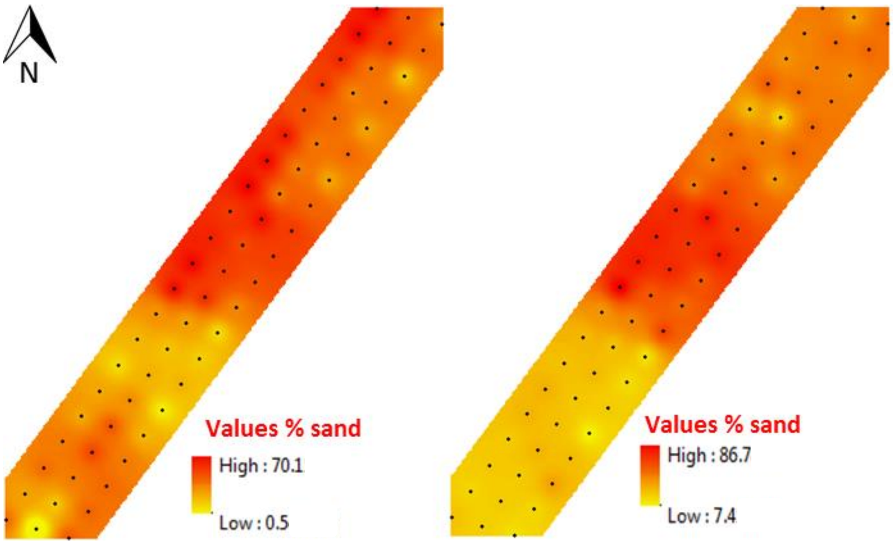


Figure 2.34. Soil Sand content as a percentage of the mineral component of the soil, mapped at 0 – 30 cm depth (left) and 30 - 60 cm depth (right).

Bulk density values over the whole field were ranged between 0.1 to 0.3 g / cm^3 with a mean value of 0.2 g / cm3 (Table 2.13). The map showed the field bulk density almost split into two zones; low and high (Figure 2.35). This was generally the opposite trend to the organic matter content and similar trend to the sand content of the soil (see Figures 2.30 and 2.34).

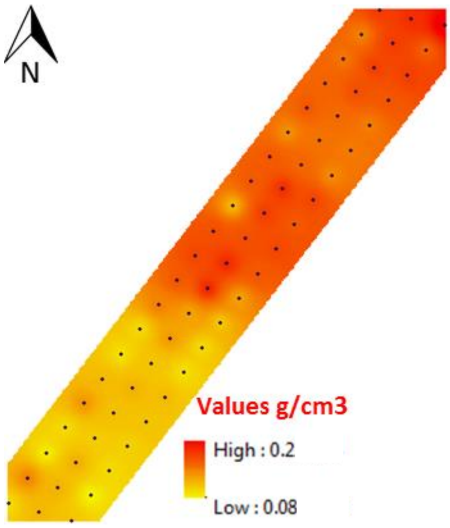


Figure 2.35. Soil dry bulk density g / cm^3 at 10 – 20 cm.

Bulk density was the main soil factor that correlated with the yield but in a negative trend (Figure 2.36).

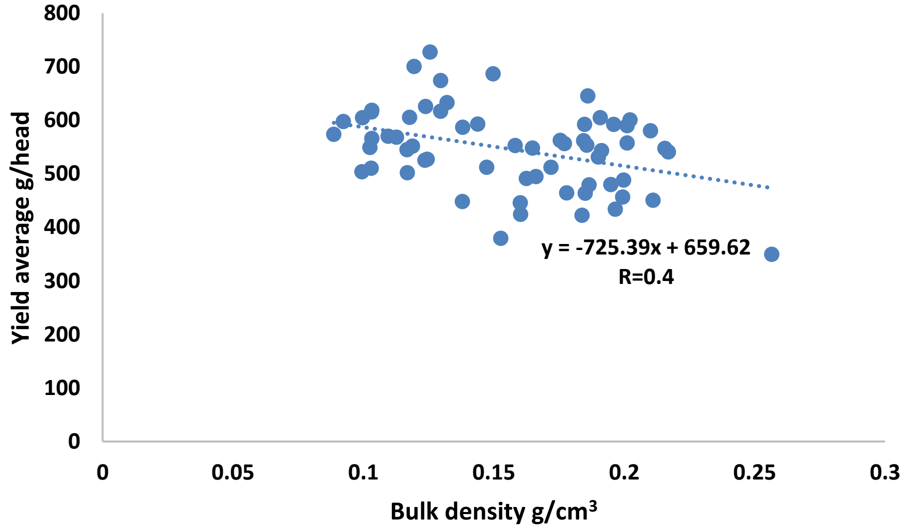


Figure 2.36. The correlation between bulk density g / cm^3 and trimmed head yield of FT3 for n = 63, (P < .001).

Penetration resistance values were variable across the field and did not correlate with any other soil or crop parameters. The map did not show any particular trend (Figure 2.37)

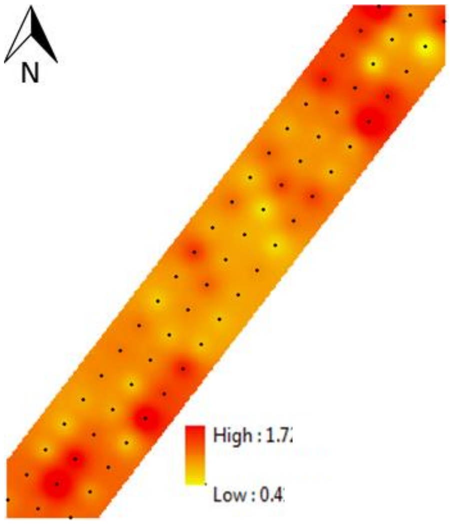


Figure 2.37. Penetration resistance map for the top 20 cm, mapped using ArcGIS, classified into 10 classes (left) and 3 classes (right).

c) Modelling trimmed fresh weight

Running the Multilinear Regression Analysis with Feature Selection (MRAFS) by including all the variables against trimmed fresh weight for FT3 and FT4 identified bulk density as the strongest predictor of trimmed head fresh weights (Table 2.15) followed by silt concentration of the mineral fraction then total nitrogen at the top soil for FT3, and total nitrogen then silt at the subsoil for FT4. The analysis also showed that the interaction between organic matter in the top and the sub soil with nutrients, and the interaction of N with P and K from the two soil depths influenced the yield (Topsoil in this experiment is considered to be 0 - 30 cm and subsoil is 30 - 60 cm).

Table 2.15. The strongest predictor variables for lettuce yields identified using MRAFS analysis results.

	R^2	Adjusted R^2	RMSD*	Variables**
FT3 trimmed head weights	0.83	0.80	51.12	BD, Silt1, N1:P1, P1:OM2, N2: K2, OM2: K2, OM1: K2, N1:P1:OM2, P1:OM1:OM2, N1:P1: OM1:OM2
FT4 trimmed head weights	0.65	0.60	60.98	BD, N1, Silt1, N1:P1, P1:OM1, P1:OM2, OM1:OM2, OM1:OM2: N2

*Root mean square deviation; the average value of the residuals of the actual and the predicted values. The higher the RMSD value the less accurate is the model.
**BD (bulk density), Silt, N (total nitrogen), P (total phosphorus), K (total potassium), OM (organic matter), 1 denotes (0 - 30cm) and 2 denotes (30 - 60 cm).

From Table 2.15, it could be seen that the fitted model for FT3 accounted for 83% of the yield variation. Whereas, the fitted model for FT4 is accounted for 65 % of the yield. The RMSD value for FT3 was also smaller which also indicates a better accuracy for FT3 model in comparison with FT4.

Bulk density was the main predictor that was most highly associated with trimmed head fresh-weights in both FT3 and FT4. However, bulk density is known to be influenced by soil texture, which may vary across the field (Ruehlem and Korschens, 2009), as well as being affected by the level of the organic matter in the soil at any one location (Dexter, 2003a; Ruehlem and Korschens, 2009). Therefore, the same analysis was followed with the exclusion of bulk density. The results after excluding bulk density showed that the topsoil total phosphorus (P1), subsoil total potassium (K2), and sand (Sand1) were the strongest three predictors (from the strongest to the weakest) for trimmed fresh weight for FT3 and topsoil total phosphorus (P1), organic matter (OM1) and top soil silt (Silt1) were the strongest three predictors for FT4 (Table 2.16). It can also be seen from Table 2.16 that there has been a slight reduction of the model accuracy as indicated by R^2 and RMSD values.

Table 2.16. The strongest predictor variables for lettuce trimmed weight after excluding bulk density from the analysis for FT3 and FT4. And R^2 and RMSD.

	R^2	Adjusted R^2	RMSD*	Variables**
FT3 trimmed head weights	0.81	0.79	53.87	P1, K2, Sand1, P1:OM1, N1:OM2, P1:OM2, OM2: K2, OM1:N2, N1:P1:OM1, N1:OM1:OM2, OM2:N2: K2, OM1:OM2: K2
FT4 trimmed head weights	0.66	0.60	58.69	P1, OM1, Silt1, P1:OM1, OM1:OM2, Sand2:Clay2, P1:OM1:OM2, OM2:N2: K2

*Root mean square deviation; the average value of the residuals of the actual and the predicted values. The higher the RMSD value the less accurate is the model.

**BD (bulk density), Silt, N (total nitrogen), P (total phosphorus), K (total potassium), OM (organic matter), 1(0-30cm) and 2 (30-60 cm).

d) Soil particle sizes

For each soil sample, a chart of particle size distribution was generated (Figure 2.39) where the count and sizes of the particles from 0.5 to 2000 µm were measured. The sizes were divided into 100 bins, where each bin contains the count for that particle size range.

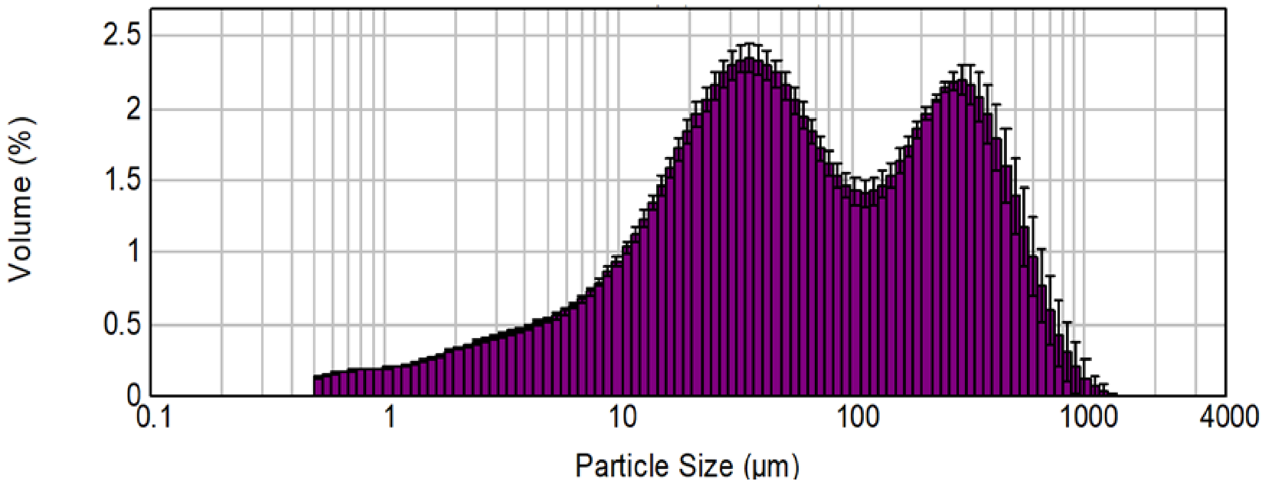


Figure 2.38. Particle size distribution for an example sample showing the frequency of each particle size between 0.5 and 2000 um (micrometres) spread over 100 bins. The bars show the means of the particle frequency for each size and the error bars show the standard deviation.

This enabled the investigation of specific particle sizes with their distribution for each sample using the same statistical analysis, to test whether certain particle size ranges influence the trimmed fresh weight more than the standard designated ranges for sand, silt, and clay sizes (Table 2.17).

Table 2.17. Standard soil particle size distribution.

Soil Texture component	Particle size in mm	Particle size in µm
Clay	< 0.002	< 2
Silt	0.002 - 0.06	2 - 60
Sand	0.06 - 2	2000

(Source; Adapted from Brady *et al*., 2006)

The raw data of soil particle sizes were used in the MRAFS analysis without segregating them into the size ranges that are shown in Table 2.17. The results showed that for the topsoil texture, the finest clay particles from (0.5-0.6 µm) appear to have the strongest effect on FT3 yield. Whereas, the finest silt particles (2.01 to 2.6 µm) seem to have the strongest effect on FT4 yield. These results are presented in Tables 2.18.

Table 2.18. Particle size predictors for lettuce trimmed fresh weight derived from the multilinear regression analysis with subset selection for the topsoil (0-30 cm)

	R^2	RMSD	Variables (µm)
FT3 trimmed head weights	0.69	65.23	"0.5" "0.595” “2.194” “2.611” “3.39" "4.034” “11.458"
FT4 trimmed head weights	0.62	62.77	"2.011” “2.611” “4.801” “9.628” “11.458" "19.311" "21.066"

For the subsoil texture, the analysis showed that the fine silt particles of the size 2.5219 µm was the strongest predictor of trimmed fresh weight for both FT3 and FT4 (Tables 2.19 and 2.20).

Table 2.19. Particle sizes predictors for lettuce trimmed fresh weight derived from the multilinear regression analysis with subset selection for the subsoil (30-60cm)

	R^2	RMSD	Variables (µm)
FT3 trimmed head weights	0.34	85.24	"2.5219" "8.0902"
FT4 trimmed head weights	0.53	66.92	"2.5219" "2.8038" "0.0618" "0.0687" "0.0764" "0.0944" "0.1167" "0.1298"

Table 2.20 shows how each particle size predictor fitted within the standard particle sizes classification.

Table 2.20 The class of the strongest yield predictors of particle size ranges (within their texture components).

Soil Texture component	Particle size in mm	Particle size in µm	Topsoil's strongest yield predictors of soil particle sizes	Subsoil's strongest yield predictors of soil particle sizes
Clay	Less than 0.002	Less than 2	0.5 µm for FT3	
Silt	0.002 - 0.06	2 - 60	2.01 µm for FT4	2.5 µm for FT3 and 2.5 µm for FT4
Sand	0.06 - 2	2000		

The analysis was repeated after replacing the sand, silt and clay data with the raw particle sizes data. The results were markedly different to previous model (Table 2.21). The R^2 values were lower and RMSD's were higher for both FT3 and FT4, suggesting a reduction in the model accuracy (see Tables 2.15 and 2.16 for comparison). The particle size ranges of interest (the strongest yield predictors of particle size ranges); 0.5, 2.5219 and 2.011 were not present in the new model. Even though they were the most important sizes when only texture is tested, it did not mean that other particle sizes should not be considered to explain more variance in yield. Therefore, this model can be considered as less predictive and this suggests that the variance is accounted for by other factors rather than the particle sizes of the soil mineral fraction.

Table 2.21. The strongest predictor variables for lettuce trimmed weight after replacing the sand, silt and clay data with raw soil particle-sizes data in the MRAFS analysis for FT3 and FT4. And R2 and RMSD

	R^2	RMSD	Variables (µm)
FT3 trimmed head weights	0.77	61.6	"OM1" "N2" "1.549" "1.844" "2.194" "2.611" "3.39" "4.034" "11.458"
FT4 trimmed head weights	0.73	66.51	"P1" "P2" "V0.5" "V2.5219" "OM1:N2: K2" "OM1: K2: P2" "OM2:N2: K2" "OM1:OM2: N2" "OM1:OM2: P2" "OM1:OM2: N2: K2" "OM1:OM2: K2: P2"

Profile pits:

There was an apparent difference in soil structure between the North and the South regions of the field as revealed by the excavated soil pits in soil structure. (Figure 2.41)

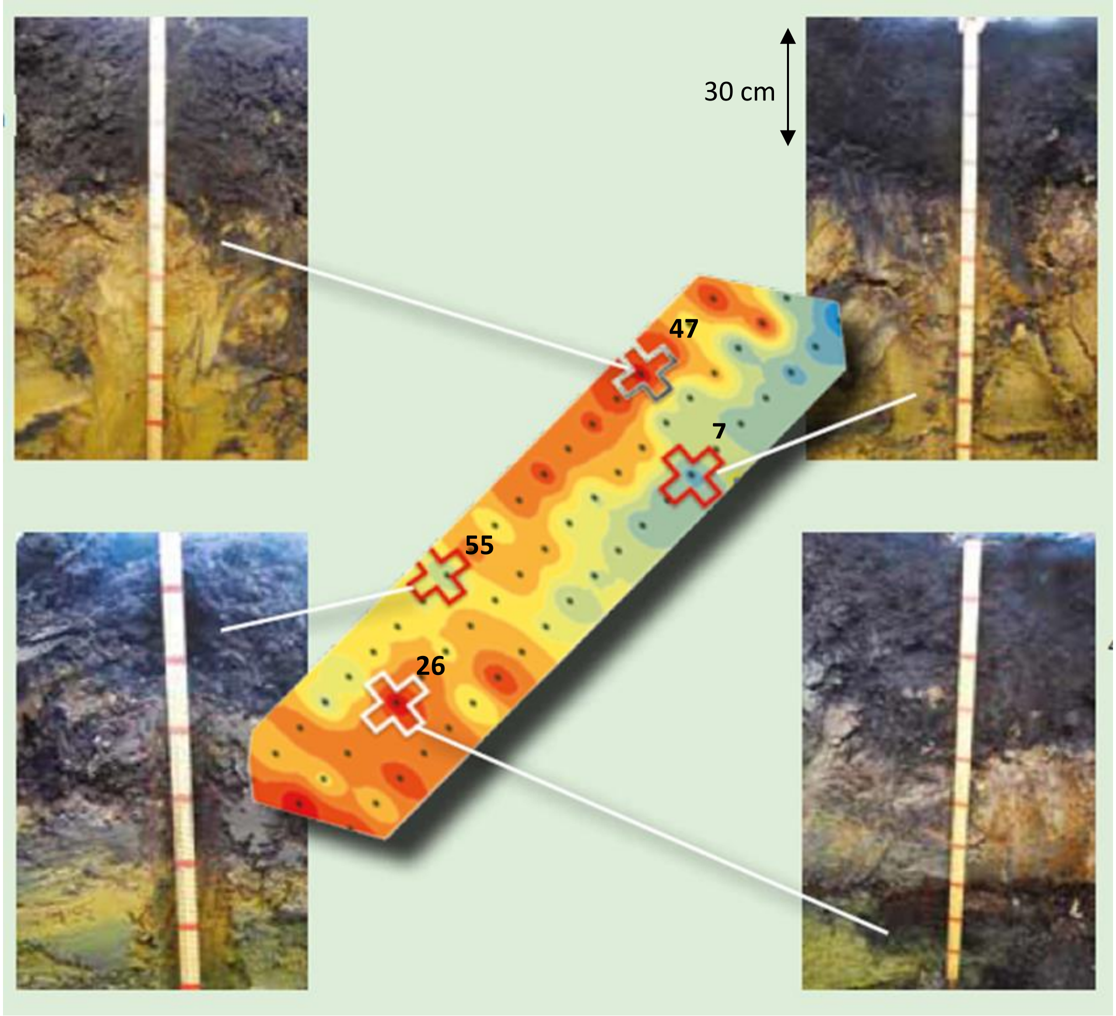


Figure 2.39: Pictures of the profile pits excavated in Redmere P57. In the sampling locations 7, 26, 47 and 55. Locations 7 and 55 (blue areas on the map - low yield). Locations 26 and 47 (red areas on the map -high yield). The red bands on the ruler denote 10 cm intervals

Location number 7 (low yield)

Horizon 1: from 0 t0 30 cm, dark organic matter layer, penetration resistance was 1.2 kg f / cm^2 (Kilo gram force per square centimeter) on average, root residue visible.

Horizon 2: from 30 and down to 60 cm. lightly coloured sandy soil with occasionally gray or orange spots. Penetration resistance was 2.4 kg f / cm^2 on average.

Horizon 3: from 60 and down to a 100 cm depth, grey to greenish colour.

Location number 26 (high yield)

Horizon 1: from 0 to 40 cm of dark organic matter layer. Some old root residues were visible. Penetration resistance was 0.9 kg f / cm^2 on average.

Horizon 2: from 40 and down to 70 cm lightly coloured sandy layer of soil. Penetration resistance was 1.7 kg f / cm^2 on average.

Horizon 3: from 70 and down to 100 cm another layer of red soil with occasional of blue clay, and yellow and greyish patches. Penetration resistance was 1.4 kg f / cm^2 on average.

Location number 47 (high yield)

Only two horizons were identified.

Horizon 1: From 0 to 30 cm of dark brown friable organic matter layer, with few old root residues were visible. Penetration resistance was 1.5 kg f / cm^2 on average.

Horizon 2: From 30 and down to 100 cm, one layer of yellowish coloured soil of penetration resistance 2.3 kg f / cm^2 on average.

Location number 55 (Low yield)

Horizon 1: For horizons were identified in this location. From 0 to 30 cm of dark brown friable organic matter layer. Penetration resistance was 2.6 kg f / cm^2 on average.

Horizon 2: from 30 to 45 cm, a layer of red soil. Penetration resistance was 2.2 kg f / cm^2 on average.

Horizon 3: 45 to 60 cm a layer of grey soil with penetration resistance 1.7 kg f / cm^2 on average.

Horizon 4: from 60 and down to 100 cm. a yellow layer of soil darkening to grey to blue colours at the bottom. Penetration resistance 1.7 kg f / cm^2 on average.

2.2.3 Discussion:

Yield- There was no significant difference in the marketable yield of trimmed head weights between FT3 and FT4, and the maps of the two harvests showed similar spatial patterns of variability where most low yielding and high yielding locations remained the same in both harvests. This was particularly evident from north to south and from east to west in both maps. The spatial yield patterns were consistent for two successive lettuce crops. This suggests that there are underlying soil properties influencing yield distribution regardless of seasonal factors such as soil type. This should therefore be useful information because if it could be mapped it could provide a valuable indicator of crop growth across the field for subsequent crops.

Marketable head weights in the studied field ranged from 314 g to 716 g per head with an average of 531 g / head for FT3 and (from 288 g / head to 818 g / head) with an average of 559 g / head for FT4. The variability between individual heads of the same location (plant to plant variation) was eliminated as a source of across the field variation at this stage due to small CV % values for these data in comparison with the overall spatial yield variability across the field and the difference between the high yield bands and the low yield bands.

The spatial variation of lettuce and wheat yields were compared to examine whether the spatial variation patterns of both yields are similar and hence, whether the controlling factors were the same. However, there was no statistical correlation between the two yields and no resemblance between the two yield maps. This could be due to the difference in rooting depths, development stages and crop duration between these two crops; wheat is a long season, non-irrigated crop and lettuce is a short season, irrigated crop with intensive inputs. The relatively short crop duration for lettuce of 5 - 8 weeks from transplanting to maturity contrasts with that of wheat i.e. 7-11 months. As a consequence of the longer growing period, long season crops such as cereals access a greater depth of soil and the yield is more dependent on the sufficient extraction of subsoil water, whereas mature lettuce stands in the field for a very short term and the final yield is less dependent on the subsoil water and more sensitive to external factors during early stages (Costigan and McBurney., 1983). Moreover, yield maps can be temporally different year to year

Soil electric conductivity- ECa maps of both shallow and deep ECa showed mostly a similar pattern across the field. Both maps were created using the same method for comparison (inverse distance weighting in ArcGIS, classifying the data into 10 classes using the geometric intervals method and using the same colour ramp). In this studied area, both layers of soil (shallow and deep) had similar range of ECa values despite 1 mS / m difference in the highest ECa values and 0.6 mS / m difference in the lowest ECa values. This difference is very unlikely to cause substantial difference in the colour range. The regression equation showed that 38 % of the variation in deep ECa could be predicted by the variation in the shallow EC. However, there was no correlation between ECa at either depth with the yield.

Despite the strong correlation between shallow ECa and deep EC, and despite the similarity between the two depths and their distributions, ECa did not correlate at either depth with the yields. Deep Soil ECa however, showed some correlation with organic matter, total nitrogen and potassium at both depths, bulk density as well as with sand and silt content. Shallow ECa showed some weak correlation with potassium at both depths as well as with organic matter at the top depth of the soil. The moderate correlation between deep ECa and soil moisture and clay content conforms to previous research findings, where ECa (or ECa) was suggested to be mainly a function for clay and moisture contents of the soil (De Benedetto *et al.,* 2000; Godwin and Miller, 2003; Brevick *et al*., 2006). However, when considering the profile pit investigations there did appear to be differences.   As the ECa measurements are taken at such wide bout widths, 24m, and 12m long bouts, variation across the field may not be adequately represented by these scans.

In this specific field, ECa scans did not correlate with lettuce crop yield. This conforms to the results of the 2014 experiments (FT1 and FT2), suggesting that ECa scans are not very useful for predicting lettuce yield.

The correlation of ECa with crop yield is not consistent due to ECa being affected by soil properties that might not necessarily affect the yield in a certain field or in certain zones of a field as noted by Corwin *et al*., (2003). For example, in this field ECa could be a result of consistent or non-consistent soil properties that have not been measured or do not correlate with lettuce yield such as the depth of top soil or the depth of a water table (Corwin and Lesch, 2005).

Organic matter- Organic matter was significantly greater in the surface soil than the subsoil with strong correlation between the two and similar spatial distribution. Organic matter levels within the top 30 cm of the soil ranged between 21 and 53%, which is considered as fertile soil (Loveland and Webb., 2003) and “marginally high” to “high” in organic matter (Thompson, 2007). However, these are still considerable variations and might result in effect on nutrient and water holding capacity, soil structure and drainage, etc. With similar range of variation (about 32 % difference in OM), the subsoil organic matter content at 30 – 60 cm ranged from 6 % to 38.7 %. A soil with 6 % organic matter is classified to be on the border between mineral and organic mineral soil. Meanwhile the soil areas with 38.7 % of organic matter is classified as Sandy peat or loamy peat (Natural England, 2008). The difference in the organic matter concentrations between the two soil depths may predominantly arise from greater breakdown and decomposition activity due to better aeration in the topsoil in comparison to the subsoil (Davies *et al*., 1993). The similarity in OM spatial pattern (from the north to the south orientation) suggests that the organic matter in the 0 - 30 cm layer influences the OM at the 30 – 60 cm layer, this could also indicate further spatial variation in soil texture. Qiu *et al*, (2016) found a correlation between the spatial variability in organic matter and the variability in soil texture and reported that variability in soil texture is a key factor influencing the in-field variability in organic matter. However, the difference the range of values of the organic matter between the two depths in this study makes the comparison between the two maps of limited benefit.

Both soil ECa and OM values were greater in the southern part of the field in comparison to the northern part of the field. This could be explained by possible effects of the organic matter content on the ECa readings, via its effect on soil moisture properties which in turn affect the conductivity (Stadler *et al*., 2015)

Bulk density- Bulk density values over the whole field ranged between 0.1 to 0.3 g / cm^3 with a mean value of 0.2 g / cm3, which is considered normal for organic soils due to the markedly light weight of organic matter when dry (Brady *et al*., 2006). In this study, bulk density correlated negatively and significantly with clay which conforms to a previous study (Ruehlmann and Korschens, 2009) that reported a significant negative relationship between soil bulk density and clay content. The spatial distribution of bulk density was similar to that of organic matter but distributed in the opposite direction, i.e. bulk density was low where organic matter was high.

Bulk density also correlated negatively with lettuce yield, which, for a relatively loose soil with high levels of organic matter, contradicts with the findings of an earlier study (Arvidsson, 1998) that reported an increase in barley yields in soils with higher organic matter under traffic due to the organic matter increasing the loosened soil need for compression to improve the yield, especially that in this study bulk density correlated negatively with organic matter which conforms with the study of Arvidsson, (1998)

Nutrients- Of the three nutrients measured at the two soil depths, lettuce yield correlated only with total K and total N at the 30 - 60 cm soil depth.

There was a strong correlation between the topsoil and subsoil total nitrogen, but the level of total N was significantly higher in the top 30 cm of the soil. This may be due to naturally higher organic matter content and improved aeration and mineralisation in topsoil (Brady and Weil., 2006, or due to limited leaching of applied N into the subsoil with drainage water).

Total K, however, was significantly higher in the subsoil than in the topsoil with a strong correlation between the two levels of K. The difference in K between the two depths and the fact that total K was lower in the topsoil could be a result of crop root uptake and farming practices or manipulation to adapt to crop needs such as fertilising the soil or incorporating the previous crop residue during tillage (Brady and Weil., 2006). The correlation between the yield and K agrees with an earlier study (Costigan and McBurney, 1983) which associated improved lettuce growth with native potassium and phosphorus in the soil. However, in this study, the correlation matrix showed no relation between the yield and the total P.

MRAFS results discussion

Bulk density was the strongest predictor of trimmed head fresh weights as per the MRAFS analysis that included all studied parameters against the yield, followed by silt concentration of the mineral fraction then the interaction of the total nitrogen with the total phosphorus at the top soil for FT3, and total nitrogen then silt at the subsoil for FT4. The analysis also indicated a notable influence for the interaction between organic matter at both soil depths with nutrients and the interaction of N with P and K on the yield.

Bulk density was excluded from the model at a second stage before repeating it, because its scatter plot against FT3 yield showed that the bulk density data were categorized into three groups of values (two main groups and one other small group), suggesting it should be considered as a categorical variable. Furthermore, bulk density is known to be influenced by soil texture and that may vary across the field (Ruehlem and Korschens, 2009) as well as being affected by the level of the organic matter in the soil at any one point (Dexter, 2003a and Ruehlem and Korschens, 2009). Therefore, the same analysis was followed with the exclusion of bulk density.

The results after excluding bulk density showed that the topsoil total phosphorus (P1) was the strongest predictor of the yield for both FT3 and FT4, which agrees with an earlier study (Costigan and McBurney, 1983) and contradicts with the results of the correlation matrix which showed no correlation with P. The second and third strongest predictors for the yield was subsoil P and topsoil Sand content for FT3 and topsoil OM and Silt for FT4.

The FT3 model was stronger due to its higher R^2 values and lower RMSD values, moreover, the yield in FT3 was collected instantaneously with soil data.

The results showed that for the topsoil texture, the finest clay particles from (0.5-0.6 μm) appear to have the strongest effect on FT3 yield. Whereas, the finest silt particles (2.01 to 2.6 μm) seem to have the strongest effect on FT4 yield. For the subsoil texture, the analysis showed that the fine silt particles of the size 2.5219 μm was the strongest predictor of trimmed fresh weight for both FT3 and FT4

At both layers, the analysis showed that the finer particles in the soil had stronger effect on the yield, which is likely due to the larger surface area where the fine clay particle sizes have more ability to adsorb more nutrient, gases and moisture with their specific surface phenomena (Brady *et al*., 2006) - their ability to hold cations is a key part of soil fertility. Clay was much lower in the subsoil than in the topsoil, which probably explains why the strongest predictor of the yield from the subsoil particles were the finest silt particles.

Replacing the sand, silt and clay contents in the analysis with the actual particle sizes, and in comparison, to the first and second analysis (including and excluding the bulk density), continued to show topsoil phosphorus (P1) as the strongest predictor of the FT4 in addition to P2 as a second predictor for FT4. Moreover, it showed the topsoil OM1 and subsoil N2 to be the strongest and the second strongest predictor for FT3. However, it also resulted in reduction of the model accuracy by reducing R^2 and increasing the RMSD values. This could also be due to separate the organic matter from the texture effect which is an important component of the texture effect.

Considering that nutrients are the most practically modifiable inputs of the studied properties, a model was fitted to the nutrient data to test which nutrient predictor variables provided the highest (predicted) yield when it was increased while keeping the rest of the variables constant. This allowed examination of the influence and the scale of the response. The results showed that the highest yield response can be achieved when the subsoil nitrogen (N2) was increased by 0.5, 1, 1.5 and 2 mg kg-1 respectively, and while keeping the other variables constant. The model was used to predict yield by using 20 % increase of the topsoil nitrogen. The topsoil nitrogen here was chosen considering that it is an easily achievable practice in the field and due to the highly predicted yield response to nitrogen at both depth generally.

The predicted trimmed fresh weight increased with the increase of total nitrogen in certain locations within the field whilst it decreased in others.

Calculating the values using one of the low yield sampling locations (location number 3) as a reference point was done in ArcGIS by increasing the levels for individual variables, by 5 %, 10 % and 20 % each time for the model that included bulk density and for the strongest predictor variables in this model, there has been a yield decrease with the increase of bulk density and silt content. Whereas, Nitrogen increase, however, had no effect on yield response. The model that excluded bulk density showed a modest yield increase, most notably when increasing P1, K2 and Sand1, whereas increasing OM for the topsoil had negative effect and increasing it in the subsoil had negligible or no effect which conforms to Costigan (1986) study that found a negative effect to soil organic matter on the relative growth rate of lettuce, and the percentages he reported were 28.5 % and 45.7 % of organic matter. However, Costigan's study only comparing lettuce growth rate on a variety of soil types including two organic soils and there weren't enough organic matter data to support these findings. Costigan study did not explain why these levels of organic matter were associated with poor crop performance however, it suggested that an increase in cation exchange capacity of the soil that had possibly reduced the availability of some micronutrient cations to the plants or some unfavourable increase in microbial activity or higher soil temperatures due to darker colour of the soil.

Field variation:

In terms of the yield and soil texture in the studied field there were two different scenarios where the field could be divided into two areas:

1) Area 1: the southern part of the field, where the yield was high in comparison to the northern part of the field. In this part of the field, the organic matter percentage was higher along with some of the other yield-influencing factors, such as K, N at 30-60, and soil moisture in addition to soil EC, but excepting bulk density and sand content.

2) Area 2: the northern part of the field had more complex results that do not support a simple explanation of the crop performance. The yield in this part of the field was lower than the southern part and it also differed from the west to the east (decrease). The west to east yield trend matched the sand trend and could therefore be a key to the yield (both sand and yield decreased from the west to the east). Organic matter was lower on the shallow map at that part of the field, with between 21-31% organic matter content, which is still considered as fertile soil (Loveland and Webb, 2003). There are several interactions between soil properties and soil nutrients which need further investigation before the complexity of these effects can be explained.

Profile pits:

The difference in soil structure between the northern and the southern part of the filed was characterised primarily by the depth of the organic matter and the topsoil layer.

In the northern part of the field, the depth of the top soil layer in the two excavated pits, appears to extend to 30 cm, followed a layer of blue clay with unfavorable aeration conditions (Brady and Weil, 2006). No traces of root growth were found in the second layer. However, one of these two location had high yield (number 47) and the other had low yield (number 7), indicating that the structure did not coincide with the yield however, the high yield location fell in the area with the higher sand content which suggests that the sand content in this location (the eastern part of the northern half of the field) played a role in enhancing the aeration and hence the higher yield in that part of the field.

Meanwhile, in the southern part of the field, the topsoil and organic matter layer appears to be deepened by 10 more centimeters in one location and by another 20 cm by red soil in another, allowing deeper root penetration and better drainage (Brady and Weil, 2006). One location in this part had low yield (number 55) and the other had high yield (number 26). The location that had the low yield can be explained by that fact that that it fell outside the high sand area therefore the drainage and aeration problem was not mitigated in this location similarly to high yield location (number 47) that was on the same sampling line, or the other high yield location in the same (southern part of the field – number 26) that had another deep red soil layer at the bottom that possibly improved aeration and drainage.

2.2.3.1 Conclusions:

- The variability pattern of lettuce yields was consistent over the zones of the two crops, suggesting that yield distribution was mainly influenced by soil properties. Yield variation was mainly driven by underlying soil properties rather than by seasonal variation in moisture and weather conditions.
- Although variable field zones could be identified using soil ECa scans or soil properties' maps along with the yield maps, there was no statistical correlation of yields with ECa scans and there was no conformance or correspondence between the maps of the two parameters.
- Either shallow or deep ECa maps can be used to identify variable field zones due to strong correlation between the two layers of readings and also due to the considerable correspondence between the two maps.
- Organic matter variation played a key role in the overall soil variation in the field through a complex relation with organic matter, texture and water holding properties.
- For the first crop bulk density was the strongest predictor of trimmed head fresh weights, followed by silt concentration of the top soil.
- For the second crop, bulk density was also the strongest predictor of trimmed head fresh weights followed by total nitrogen of the subsoil, then the silt concentration of the subsoil.
- The total phosphorus in the topsoil was the strongest predictor of the yield for both crops after bulk density was excluded from the model.

2.2.3.2 Limitations:

A replication of this experiment might be useful when greater scanning intensity could be ensured and other soil properties such as clay and moisture content could be mapped or examined at the time of the ECa scanning for comparison. A repeat of the scanning could add more accuracy to the ECa maps.

Although the nutrients analysed for this study were total nitrogen, potassium and phosphorus and do not reflect the availability of these elements, these measures can be used to indicate a general nutrient status of the soil especially with favourable levels of organic matter (Costigan and McBurney. 1983).

This complexity underlines the importance of considering the specific conditions of each field when attempting to make precision management decisions and the need for greater understanding of the interactions within soils. Once this complexity has been resolved into underlying components, the ability to predict yield may become more feasible. In this particular study site, the yield reduction in Area 1, due to the reduction of organic matter, could have been altered by the native abundancy of nutrients such as phosphorus or potassium. The availability and mobility of these nutrients requires further research where it becomes possible to view the level and influence of each key factor in the light of the levels and the interaction with of other elements.

3 Chapter 3: Investigating the effects of soil organic matter and sand content

3.1 Introduction to the hypothesises:

Experiments FT3 and FT4 showed that the in-field variability of lettuce yield was spatial. The strong correlation that was found between the two yields, and the consistency in the yield zones, where the high and low yielding zones in the first crop remained the same in the second crop, suggested that the spatial variation in the first crop could be used to predict possible management zones for the subsequent crop in the same field. The main aim of Chapter 2 was to identify a limited number of soil factors that influenced the development and the final yield of the crop. The consistency in the spatial yield patterns for two successive crop cycles, with the consistency in the overall yield of the studied area and the field, suggests that lettuce yield in the studied field was driven by soil factors that did not change between the two seasons such as bulk density and some of the soil texture components as shown in the results of Chapter 2.

Bulk density, silt concentration and total N were respectively the strongest predictors of the yield. And after excluding the effect of bulk density, the strongest predictors of the yield were; subsoil total P and Sand concentration for FT3, and Organic matter and Silt concentration for FT4. The similarity in OM spatial pattern (from the north to the south orientation), suggested further spatial variation in soil texture for this field. Qiu *et al*, (2016) found soil texture to be a key influencing factor affecting the in-field variability in organic matter. Furthermore, bulk density is known to be influenced by soil texture (Ruehlem and Korschens, 2009) as well as being affected by the level of the organic matter in the soil at any one point (Dexter, 2003a and Ruehlem and Korschens, 2009). Therefore, the effects of organic matter, silt concentration, sand concentration in addition to total N and total P on lettuce yield of trimmed heads required further investigation.

The bulk density of the soil, organic matter, silt and sand concentrations are all components of soil physical quality as frequently noted by (Dexter, 2004a; Loveland and Webb, 2003; Arvidsson 1998; De Benedetto *et al*., 2000 and Qiu *et al*., 2016). All of these factors were related to the yield as indicated by the statistical model in Chapter 2. This suggested that in the location studied, variation in lettuce yield is mainly driven by variation in soil physical quality.

Identifying the critical ranges of bulk density that affects lettuce yield within the narrow range of results (0.1 to 0.3 g / cm^3 with a mean value of 0.2 g / cm^3) found in Redmere P57 poses a challenge. Measuring bulk density alone can be very difficult as highlighted by Lark *et al*. (2014) due to the level of precision needed during the extracting and handling of the soil cores, and also due to the unavoidable disturbance that occur to the samples during this process. This makes it very difficult to use conventional bulk density assessments to identify in-field variation in bulk density within such a narrow range of values. Furthermore, the change in organic matter leads to a change in the densities of soil samples and makes comparing the physical or mechanical properties of the soil from various locations within the fields problematic. Especially that various contents of organic matter in the soil samples can result in various water contents (Dexter, 2004a). this is important because the range of variability in organic matter {organic matter levels varied considerably across the field Redmere P57; between 21 % and 53 % in the topsoil (0 - 30 cm) and from 6 % to 38.7 % in the subsoil (30 - 60 cm)}.

Organic matter plays a significant role in soil physical properties and crop yields (Arvidsson, 1998; Loveland and Webb, 2003). Arvidsson (1998) found that organic matter affected the yield and the physical quality of the soil to a greater extent in comparison with soil particle size distribution. Arvidsson investigated compaction in over a 100 field experiments in Sweden, the study lasted 11 years and each experiment lasted one year with four replicates, in soils with organic matter levels that ranged from 10 to 125 g kg^{-1} and concluded that soils with over 50 g kg^{-1} organic matter (5 %) differed in yield response of barely crop and had greater yield under the same traffic treatments in comparison with soils that had less than 30 g kg^{-1} of organic matter (3 %). And also found that organic matter reduced soil bulk density, compactness and improved porosity and air content of the soil.

Soil organic matter has a role in several key soil properties affecting water and nutrient availability; e.g. residual nutrient content, cation exchange capacity, water-holding capacity, available water content, bulk density and soil compressibility (Brady and Weil, 2006 and Davies *et al*., 1993)

Dexter (2004a) investigated mathematically physical parameters of the soil (including organic matter, bulk density and texture) and defined this “physical quality” by the microstructure of the soil and studied its effects on rootability (the potential for roots to grow within the soil). Dexter used data of soils with different textures, densities and organic matter, where the latter one ranged from 2 % to 5 % into a model that calculated S with r^2 value of 0.35 from 28 Polish top soils and 0.78 from a 91 Dutch clay soils. That soil physical quality as a whole is a better indicator of rootability than bulk density exclusively and suggested that organic matter content has a greater impact on soil microstructure than particle size (texture), particularly when there was less clay content in the soil. The study found that 1.2 % and 4.2 % organic matter to be the critical levels for soils at which aspects poor physical quality of the soil started to occur and attributed the beneficial physical properties of the soil that are necessary for agricultural production to organic matter due to its association with other factors such as reduced adverse impact of machinery and enhanced rooting intensity.

Therefore, in this chapter organic matter was chosen for further study, with the hypothesis that the variability in organic matter correlated with lettuce yield through affecting the physical properties of the soil including the water holding ability at field capacity, total water content and bulk density.

The results of the field experiments FT1 and FT3 showed that zones with the highest soil OM and clay concentration, corresponded to the highest yield whereas the zone that had the lowest yield, had the lowest organic matter content and highest sand concentration. Sand concentration was also amongst the strongest three yield predictors in FT4 after excluding the effect of bulk density. Sand as a component of the mineral fraction of the soil has significant effect on soil texture classification and texture variability plays a key role in the variability of organic matter (Qiu *et al*., 2016) and the variability of bulk density (Dexter, 2004a), therefore, the sand content of the mineral fraction of the soil texture, was chosen for further study in terms of its effect on plant growth at variable concentrations.

The aims: the aim of experiments GH1 and GH2 was to examine how the change in organic matter and sand content affects the yield and early growth through affecting moisture holding properties at field capacity, water content, bulk density of the soil. The objectives of these two experiments were as follow;

- Study the effect of variable levels of organic matter on water holding capacity and bulk density
- Study the effect of variable sand content on water holding capacity and plant growth

3.1.1 Experiment GH1: The Effect of variable levels of organic matter on soil water properties and soil bulk density

Hypothesis:

The change in soil organic matter percentage is associated with change in field capacity, total water content at field capacity and bulk density.

Null hypothesis:

The change in soil organic matter percentage does not result in any changes in the soil water content at field capacity or bulk density.

3.1.1.1 Materials and methods

A field soil known to have a very low level of organic matter was collected from Flatt Nook field, Edgmond, Shropshire (52.772710 - 2.416932). The soil organic matter was measured by the ‘loss on ignition’ method (ADAS, 1986) and the average percentage of organic matter in the soil was approximately 1.0 %. The collected soil was mixed with pure peat (12 mm grade, Bulrush Horticulture Ltd, Magherafelt, UK) to create soils with differing levels of organic matter. After collecting the soil from the field, the soil was sieved and mixed using a small cement mixer to mix the soil adequately. The mixer was used before and after adding the peat. Mixing was done by volume units and treatments are presented in Table 3.1, where a soil (or sand) unit is one of the planting pots that were used for this experiment, size 0.5 L (LBS horticulture Ltd, Lancashire, UK).

Table 3.1. Soil organic matter (OM) treatments (GH1)

Treatment	Pure peat Units	soil units	Organic Matter (%)
T1	0	10	1
T2	1	9	1%+10%
T3	2	8	1%+20%
T4	3	7	1%+30%
T5	4	6	1%+40%
T6	5	5	1%+50%
T7	6	4	1%+60%
T8	7	3	1%+70%
T9	8	2	1%+80%
T10	9	1	1%+90%

Ten pots were filled with substrate from each treatment and laid out following a complete randomised block design over six blocks. The experiment started on 28/11/2016 and finished after three weeks on 17/12/2016. The glasshouse conditions over the duration of the trial had an average day temperature 16˚C and average relative humidity 62 %. The daily conditions were logged using a tiny tag data logger (the minimum recorded daily temperature was 4 C° and the maximum was 28 C°. The minimum humidity recorded was 100 %) . The processes of collecting, sieving and mixing that the soil had undergone disturbed its structure and allowed it to dry. Therefore, in the first week of the experiment the potted soil was irrigated to saturation every day, to bind the soil particles together and improve the structure (Brady and Weil, 2006) as well as bringing the soil moisture in the different treatments to a standard status (saturation) before the start of the comparative measurements.

At the start of the second week irrigation was stopped. The pots were weighed at regular intervals every three hours for the first two days, and twice a day for the third day, during normal working hours. After 48 hours water loss became negligible for all treatments. At this point all the pots were weighed and the soil moisture was measured using a Soil Moisture Meter (Field Scout^{TM} TDR 100, Spectrum Technologies, Illinois, USA) taking two readings per pot. Gravimetric water content was calculated using the equation *{SMC = (Soil wet weight – soil dry weight) / soil dry weight}*. TDR measurements were also taken. The soil slumping level (the distance from the rim of the pot to the soil surface inside the pot) that occurred due to irrigation was also measured using a ruler to enable estimation of bulk density in the pot. The soil was then oven-dried at 105 C° until constant weight was reached (approximately 96 hours). The bulk density was calculated using the following equation {Soil Bulk density (g / cm^3) = Dry soil weight (g) / Soil volume (cm^3)}.

3.1.1.2 Statistical analysis:

The collected data were tested for normality and were analysed using Analysis of Variance (ANOVA) and correlation in GenStat 17th Edition (Payne, 2009). The significant differences were identified by Tukey multiple comparison in GenStat.

3.1.1.3 Results

a) Soil moisture content and field capacity (pot capacity)

There was no block (replicate) effect on the soil bulk density or moisture properties of the treatments. For the first 48 hours, treatments that had lower levels of organic matter (T1 to T5) lost more water than the treatments with higher levels of organic matter (T6 to T10) (Figure 3.1).

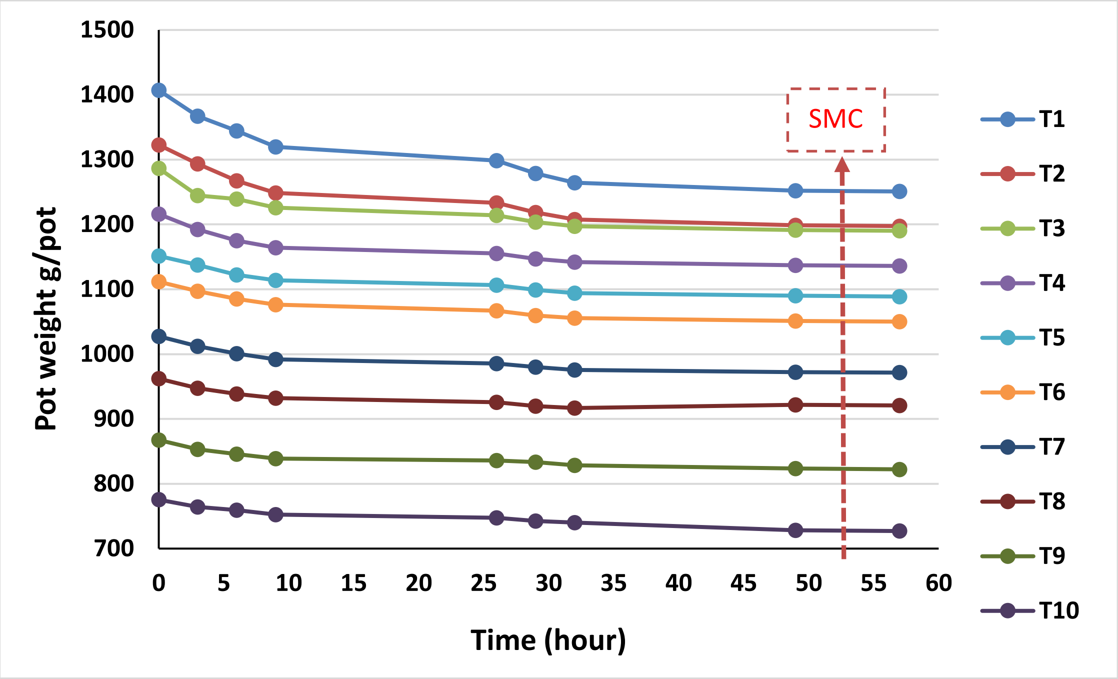


Figure 3.1. The change in pot weights for the 10 treatments over time, as measured regularly starting from saturation status and at 3-hour intervals during day time for the first two days and two readings on the third day and under free drainage. The results are averaged over 10 pots per treatment (n=10).

The weights of all treatments stabilised on Day three, where the water loss (the difference in weight between readings) was estimated to be between 1 and 2 g of lost water over 6 hours interval between the last two readings.

However, the readings for each treatment showed that treatments T1, T2 and T3 (0 %, 10 % and 20 % OM) continued to lose water until the 9th reading (last reading on Day3). Whereas, Treatments T4, T5 and T6 (30 %, 40 % and 50 % OM) approached stabilisation by the end of Day2, where the treatments lost an average of 4.5 g of water over the period of 20 hours (overnight) between Day 2 and Day 3. Treatments T7 (60 % OM) lost less than 3 g of water over the same overnight period. Treatments T8, T9 and T10 (70 %, 80 % and (90 % OM) readings showed that these treatments gained few grams of water overnight (although the pots were covered) between the 7th and the 8th readings, then stabilised again on Day 3. All the treatments lost between 1 g and 2 g between the 8th and the 9th readings on Day 3.

The total water loss between saturation and Day 3 of drainage ranged between 41 g to 156 g per pot (Figure 3.2).

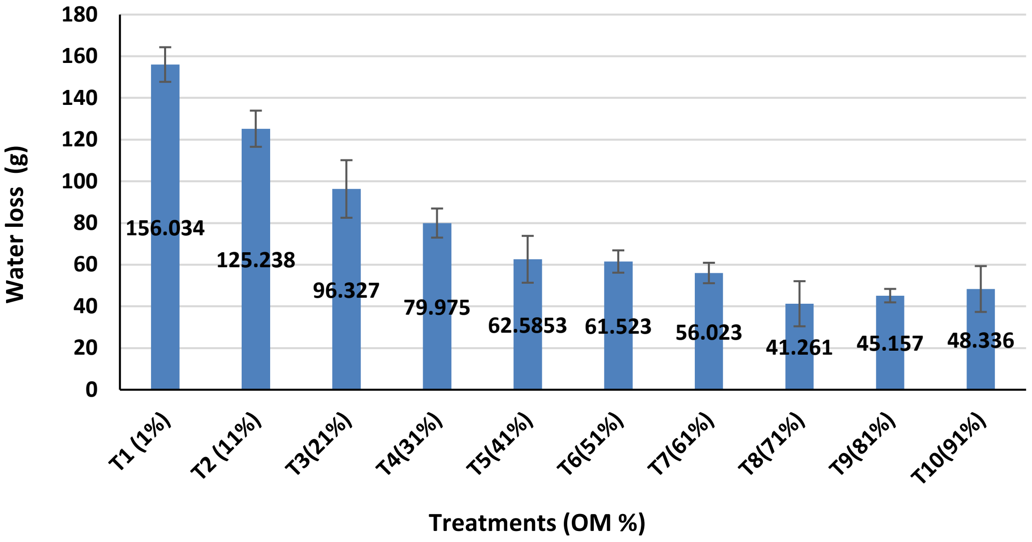


Figure 3.2. Average total water loss (g) per treatment between saturation and Day3. Error bars show standard error of the means for n = 10.

There was a strong negative correlation between the percentage of organic matter added and the amount of water lost (R = 0.9) where the variation accounted for was 83 % (Figure 3.3).

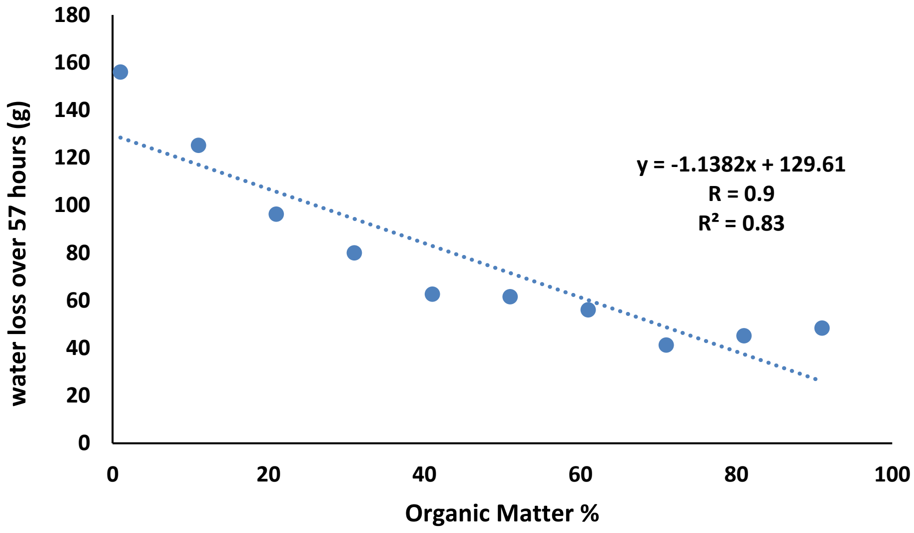


Figure 3.3. The relationship between the percentage of organic matter added to each treatment and the average of the total water lost (g per treatment) over the period of three days for n =10.

For comparing soil moisture content amongst treatments, and because soils of different types reach field capacity at variable times (speed) (Davies *et al*., 1993) day three was chosen as a reference point for comparison.

In practical farming situations, irrigation is applied uniformly regardless of variable soil types across the field. Therefore, soil gravimetric moisture content on day three was considered water content at field capacity (calculated in grams of water per pot). There was significant difference in water amongst treatments (Figure 3.4).

The significance could be viewed as three levels where from T1 to T4 (1 % to 31 % OM) was significantly different from treatments T5 to T7 (41% to 61% OM) which, in turn, was significantly different from treatments T8 to T10 (71% to 91% OM).

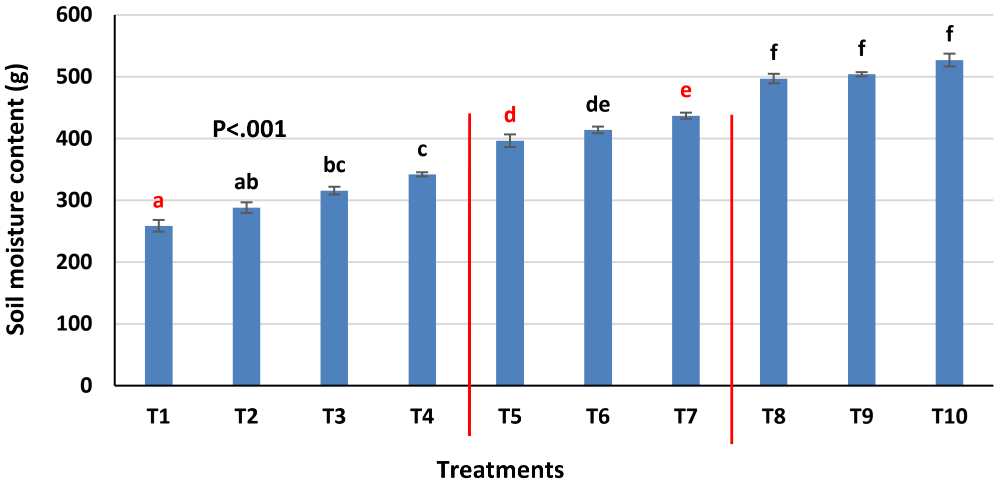


Figure 3.4. Soil gravimetric water content at FC (SMC, g of water per pot) averaged between ten pots per treatment (n=10). Error bars show standard errors of the samples for n=10.

Moisture content results for the ten treatments that were measured using the Spectrum Field Scout^{TM} TDR (VMC) differed slightly from the gravimetric results (SWC). Whilst the three general levels of moisture content could still be identified (Figure 3.5), VMC had larger error bars for some treatments (T2, T6 and T10), in comparison with SWC. The VMC showed that the 10 % difference in peat between T1 and T2 led to a significantly greater moisture content being retained by the soil of treatment T2 after three days of simulated free drainage (Figure 3.5).

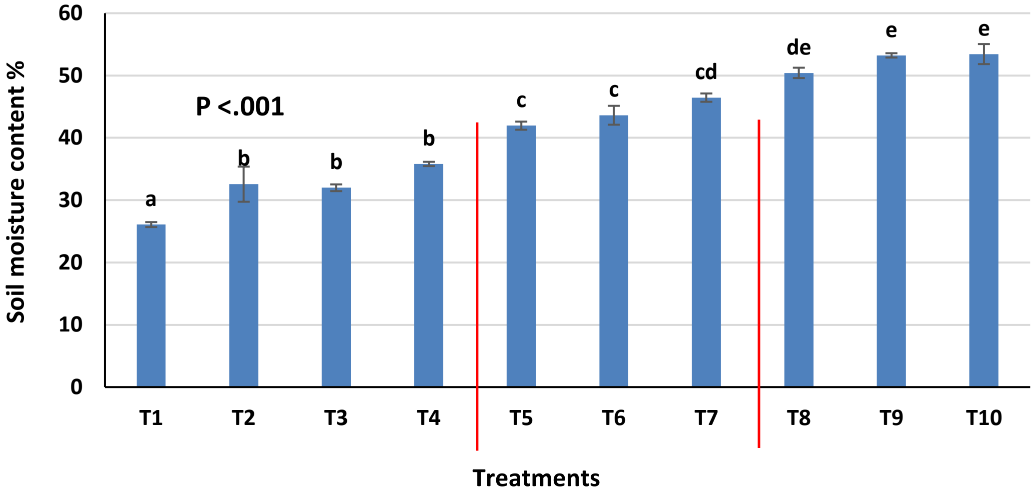


Figure 3.5. Soil moisture content as a percentage (VMC), measured using a TDR probe 3 day after saturation and free drainage. The results are averaged over 10 readings (n=10) per treatments and averaged between two readings per pot. Error bars show standard errors for the samples for n=10.

There was a strong positive correlation, R = 0.99, between organic matter content and soil moisture content at FC with 98% of variation in soil water content accounted for by the organic matter percentage (R^2 = 0.98), (Figure 3.6). The greater the organic matter content in the treatment, the greater the moisture held by the soil at field capacity (~ three days after irrigation) for that treatment (Figure 3.6). Soil VMC showed similar results. The correlation between OM % and VMC was also strong, r = 0.99, and the variation accounted for was also 98%, (R^2 = 0.98), (Figure 3.7).

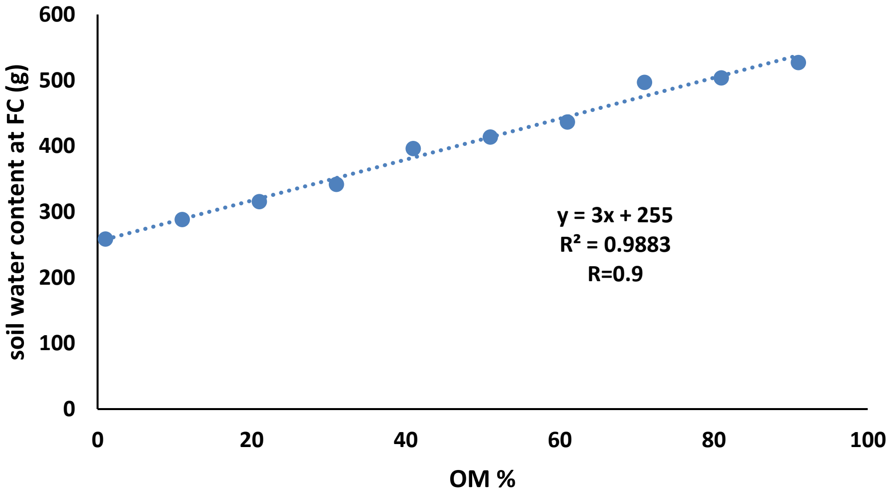


Figure 3.6. The relationship between soil gravimetric water content at FC and organic matter (n=10).

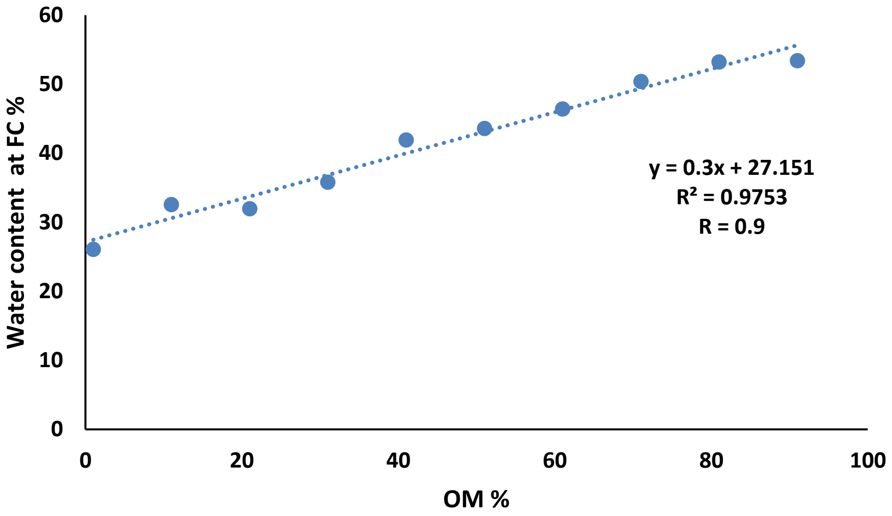


Figure 3.7. The relationship between soil volumetric water content at FC and organic matter (n=10)

b) Soil bulk density (BD)

Soil bulk density was significantly different between treatments. . There was a strong negative correlation, r = 0.999, between the OM % and the bulk density g / cm^3, (Figure 3.8), where increasing organic matter content reduced the bulk density from 1.87 g/cm^3 in treatment T1 (1% OM) down to 0.32 g / cm^3 in treatment T10 (91% OM). The R^2 of 0.99 suggests that 99 % of variation in bulk density could be explained by the variation in organic matter content (Figure 3.9).

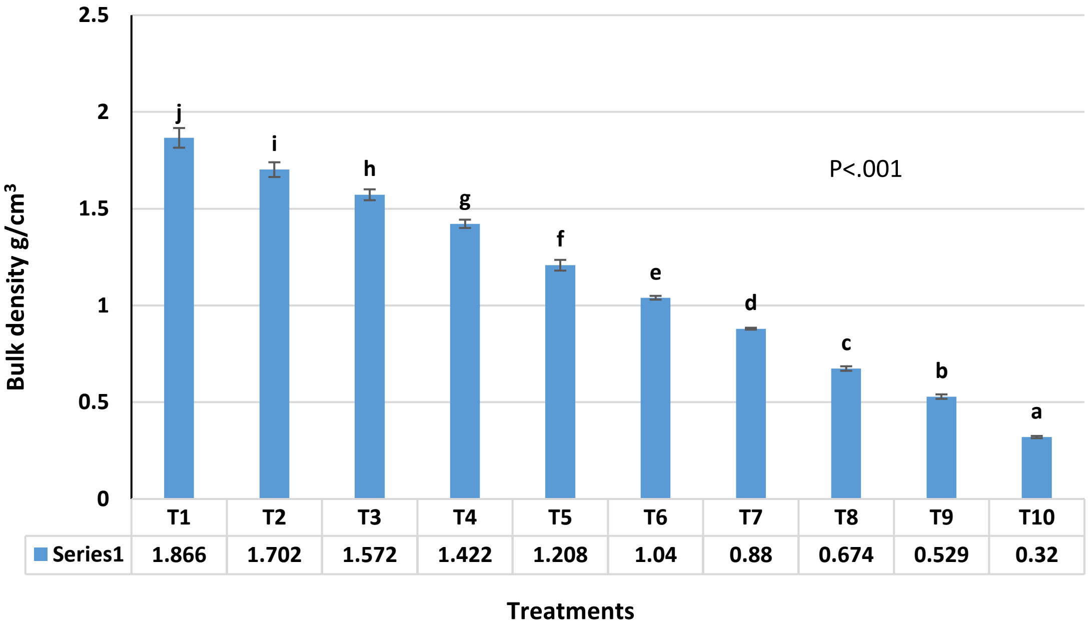


Figure 3.8. Soil bulk density (g/cm^3) for each of the ten treatments (from T1 (0% added OM) to T10 (90% added OM), averaged over ten pots per treatments (n=10). Error bars show standard error for samples for n=10.

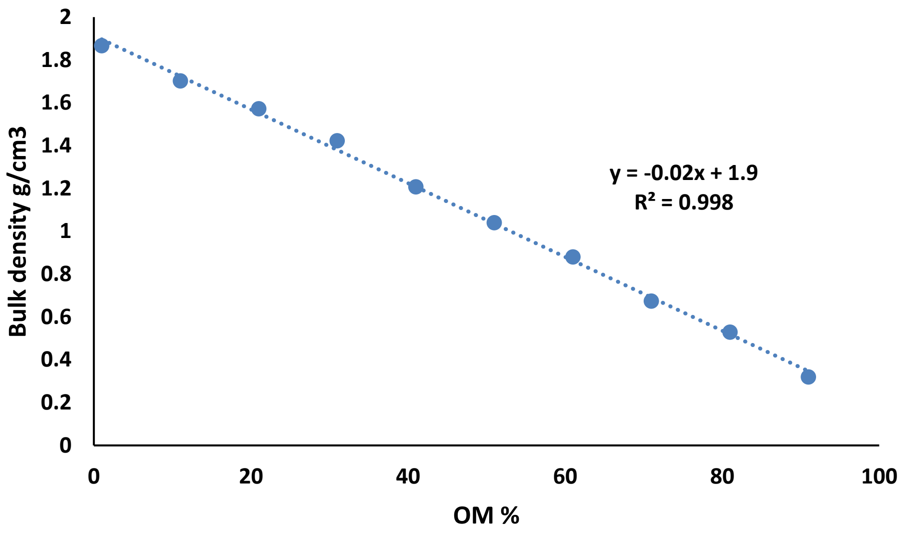


Figure 3.9. The relationship between bulk density (g/cm^3) and % organic matter content of each treatment (from T1 (0% added OM) to T10 (90% added OM), averaged over ten pots per treatments (n=10). Error bars show standard error for samples for (n=10).

3.1.1.4 Discussion

Generally speaking, the weights of all treatments was at equilibrium on Day three which exceeds the standard 24 to 48 hours soil reach field capacity in response to free drainage under gravity (Davies *et al.,* 1993) which is commonly used in conventional farming practices. This reference date was considered for comparison between the water content of variable treatments to simulate farming scenarios in practice, where conventional irrigation is applied based on a limited number of observations across the field that may or may not cover variable field zones in terms of moisture properties.

The treatments that varied in organic matter concentrations varied in the rate of water loss via free drainage and varied eventually in the total amount of water loss between the treatments and varied in the time before reaching field capacity. The treatments T1, T2 and T3 (0 %, 10 % and 20 % OM) continued to lose water until the 9th reading (56 hours after saturation). Whereas, Treatments T4, T5, T6 and T7 (30 %, 40 %, 50 % and 60 % OM) stabilised by the end of Day 2 (the standard 24 to 48 hours period). Treatments T8, T9 and T10 (70 %, 80 % and 90 % OM) appeared to have reached equilibrium before the passing of 24 hours period, and the readings showed that these treatments gained few grams of water overnight between the 7th and the 8th readings (32 hours and 50 hours after saturation), this could be due to a small amount of water remaining trapped between the bottom of the pot and the saucer top that was reabsorbed by the substrate (Cox, 1984).

On Day 3, Treatments T8, T9 and T10, held on average 75 % more water than Treatment T1. Between T1 and T2 with 10 % difference in OM, T2 held 20 % more water than T1 at field capacity.

This is important for the yield, particularly when conventionally uniform irrigation is applied. Gallardo *et al.,* (1996) found that little differences in water availability results in non-detectable differences in instantaneously measured physiological functions such as stomatal conductance and photosynthesis and suggested that the accumulation of these small and undetectable differences over the crop cycle results in differences in final lettuce yield (Gallardo *et al*., 1996)

There was a strong negative correlation between organic matter and the amount of water lost over the three days of measurements (R = 0.9) where the variation accounted for was 83 %).

Costigan (1986) found a negative effect to soil organic matter on the relative growth rate of lettuce, and the percentage he reported were 28.5 % and 45.7 % of organic matter. However, Costigan's study was unable to explain why these levels of organic matter were associated with poor growth performance and suggested the reason to be an increase in cation exchange capacity of the soil that had possibly reduced the availability of some micronutrient cations to the plants or some unfavourable increase in microbial activity or higher soil temperatures due to darker colour of the soil. The aim of Costigan's study however, was comparing lettuce growth rate on a variety of soil types including these two Lancashire organic soils, therefore, there weren't enough organic matter data to support these suggestions. Experiment GH1 showed that variability in organic matter content across the field Redmere P57 {between 21 % and 53 % in the topsoil (0 - 30 cm) and from 6 % to 38.7 % in the subsoil (30 - 60 cm)} could result in some areas of the field receiving unnecessary irrigation water and other areas of the field receiving less than their actual soil water requirements, depending on how irrigation decisions were made and where the grower's soil moisture sensors are based in the field. That is to say that variability in organic matter contents results in variability in water holding capacity and drainage, and hence, very likely to result in variable crop growth.

There was a strong positive correlation, between organic matter content and soil moisture content at FC. The greater was the organic matter content in the treatment, the greater was the moisture held by the soil at field capacity. Both gravimetric and volumetric measurements of soil water content showed similar results. The first had R value of 0.99, with 98 % of variation in soil water content accounted for by the organic matter percentage (R^2 = 0.98). And the second (VMC) had also an R value of 0.99, and the variation accounted for was also 98 %, (R^2 = 0.98) therefore, either measurement could be used

A strong negative correlation was found (R = 0.999) between the OM % and the treatment bulk densities g / cm^3, The R^2 of 0.99 suggests that 99 % of variation in bulk density could be explained by the variation in organic matter content. Increasing organic matter content reduced the bulk density from 1.87 g/cm^3 (the maximum density obtained) in treatment T1 (1% OM) down to 0.32 g / cm^3 (the minimum density obtained) in treatment T10 (91% OM). Which agrees with (Arvidsson, 1998, Dexter, 2003a and Ruehlem and Korschens, 2009) and also with finding of Chapter2- Experiment FT4. Where the spatial distribution of bulk density was inversely associated with that of the organic matter; i.e. bulk density was low where organic matter was high.

Bulk densities in Redmere P57 ranged between 0.1 and 0.3 g / cm^3 with a mean value of 0.2 g / cm^3 which is the normal range for highly organic and peaty soils (Brady *et al*., 2006). Field values were mostly below the values found in the experimental treatments despite the fact that organic matter ranges in GH1 experiment included the field ranges and exceeded them at both ends of the spectrum (higher and lower OM percentages), this could be due to the pot condition and pot irrigation method. Which makes it difficult to compare to the GH1 results. However, relatively speaking, the significant difference that was found between each two successive treatments under the addition of 10 % OM confirms the reducing effect for OM on bulk density reported in several studies including Arvidsson (1998) and Loveland and Webb (2003). In field conditions in FT3 and FT4, Bulk density correlated negatively with lettuce yield, despite the normal levels of bulk densities found in the studied field. This could be explained by the compaction effect, loss of large pores, water retention capacity of the soil (Dexter, 2004a) or hindering of root elongation within the soil (Marschner, 1995). Marschner, (1995) highlighted that soils with greater bulk density can provide the roots with greater contact with the soil, and hence better access of moisture and nutrients, which was confirmed by Arvidsson (1998) study in Sweden which found that soils with more than 5 % organic matter had greater need for compression to obtain better yields as these soils are “loose” or have low bulk density. This is to say that variability in organic matter in GH1 resulted in significantly variable bulk densities which indicates the need for variable management across the field. And with reference to field results, where bulk density correlated negatively with the yield and was the strongest predictor of the yield, this study therefore, suggests that the variability in organic matter on the yield at least through its effect on bulk density.

3.1.1.5 Conclusions:

- Variability in organic matter concentrations between the treatments resulted in variability in the rate of water loss via free drainage, the total amount of water lost, the duration to reach field capacity and the amount of water held at field capacity.
- With reference to field results, variability in soil organic matter means variability in water availability during growth and this suggests variability in the crop growth.
- Organic matter concentration as a percentage OM % correlated strongly (R = 0.999) and negatively with bulk density g / cm^3, and most of variation in bulk density was accounted for by the variation in organic matter content.
- The variability in organic matter can the yield at through both its effect on bulk density and soil water properties.

3.1.1.6 Limitations:

- The limitations of this experiment the free drainage was a basic simulation, where a more complex design could have improved the results. Covering the pots with plastic saucers did not provide a complete isolation from ambient air which must have resulted in water loss by drying and not only by drainage (drainage was not the only source of water loss.
- A repeat of this experiment would have been more useful for comparing the results and more readings over a longer period of time would have been more informative in terms of the moisture behaviour of each treatment.

3.1.2 GH2: The effect of variable sand contents on soil water properties and fresh weight at early stages of growth

Spatial variation in sand content across a field could explain some of the variation in lettuce growth through differences in water holding capacity and/or drainage. In this experiment, the effect on lettuce growth of diluting field soil with increasing amount of sand was investigated. The soil was collected from the highest yield zone of the field Redmere P36 in experiment FT1. Two different irrigation treatments were applied in this experiment to test whether variable sand proportions resulted in variable water availability to the plants and hence result in variable growth under standard or excess irrigation / rainfall, to simulate the occurrence of unpredicted rainfall or possible water logging conditions to examine how sand proportion would affect the plant growth.

The aim:

This experiment aimed to examine the influence of sand proportion on the early stages of lettuce growth and understand how this effect changes under two different soil moistures. Identify the ranges of sand content in the soil at which the water holding capacity change along with plant growth

Hypothesis

It was hypothesised that

- the proportion of sand in a soil would affect early lettuce growth.
- And that this response differs under standard and excess water application

3.1.2.1 Materials and methods

The experiment was carried out in the glasshouse using field soil from Redmere P36, the same field used in the experiment FT1. This soil was taken from the location of the highest yield (Zone C), which had the lowest sand content, the highest clay content and the highest yield. This area was chosen as it would be possible to add sand to this soil to investigate variation of sand content on a common base soil. Two hundred pots were filled with the amended treatment soils to the same level (20 pots per treatment), labelled and randomised using Latin-square design in GenStat 17th Edition.

- ***Soil amendments***

The soil was shredded using a soil shredder machine (Pneulec Services Limited - Royer machine – 99901282 with a 20.00 mm aperture sieve), to remove large soil aggregates and turn the soil into smaller granules. The soil was mixed by volume, using a small cement mixer to ensure consistency. Five texture amendments (treatments) were prepared by adding sand (Horticultural Sand, J Arthur Bowers, sharp sand, <3 mm nominal) as in table 3.2, where a soil (or sand) unit is a Deep Rose pot 8 X 11 X 18 cm (LBS Horticulture Ltd, Lancashire) and filled completely with the substrate. All five treatments were mixed again before potting-up to break the soil clods further and ensure homogeneity of the mix. Treatment A was the original unamended field soil, all treatments are shown in (Table 3.2).

Table 3.2 Texture treatments including sand and field soil proportion by volume.

Treatment	Soil%	Sand%	Number of soil units	Number of sand units
A	100	0	10	0
B	90	10	9	1
C	80	20	8	2
D	70	30	7	3
E	60	40	6	4

- ***Establishing field capacity***

Field capacity was established for the purpose of estimating the average irrigation requirements per pot (as described for GH1). Five pots were filled with soil A. The pots were put on the top of a reversed saucer that allowed free-drainage conditions. The pots were irrigated slowly to saturation, weighed (Sw) and covered. The pots then were weighed regularly until the change in weight (the weight loss) became negligible (when two successive readings became very close with less than 1 g different). After the last weight was recorded (day 6), the soil was dried in the oven at 105 °C until constant weight (for approximately 72 hours) to calculate the soil dry weight (Figure 3.10).

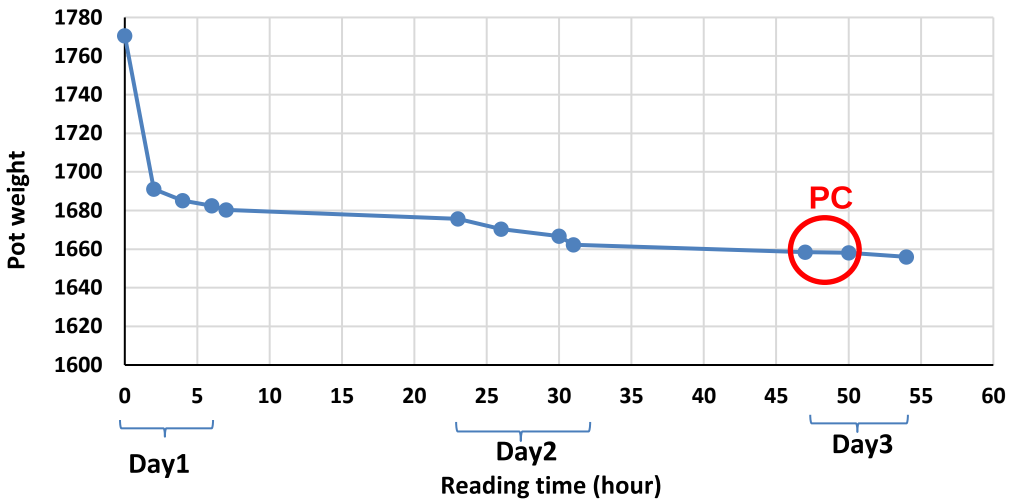


Figure 3.10. Pot capacity for the control treatment A (100%field soil) expressed as pot weight loss overtime (n=5).

After the pot weight at pot capacity was determined when the weight of the pot reached an equilibrium during day 3, soil wet weight at field capacity was calculated by subtracting the dry soil weight from the total wet pot weight. The result was 861 g of water weight as an average. Based on this weight and using the equation (1), gravimetric soil moisture content (Brady and Weil, 2006) at field capacity as a percentage (MC %) was;

$$MC = \frac{\textbf{Soil wet weight at FC} - \textbf{Soil dry weight}}{\textbf{Soil dry weight}}$$

Equation 1

Similarly, to GH1, for comparing soil moisture content amongst treatments, and because soils of different types reach field capacity at variable times (speed) (Davies *et al*., 1993) pot weight at field capacity (1658 g including 861 g of water weight) was chosen as a reference point for comparison.

Soil moisture content at field capacity (pot capacity) as weight, was 55 % of the saturated pot weight. The same method was followed to establish pot capacity for the four remaining texture treatments for further comparison between treatments. Three pots were used per treatment (Figure 3.11).

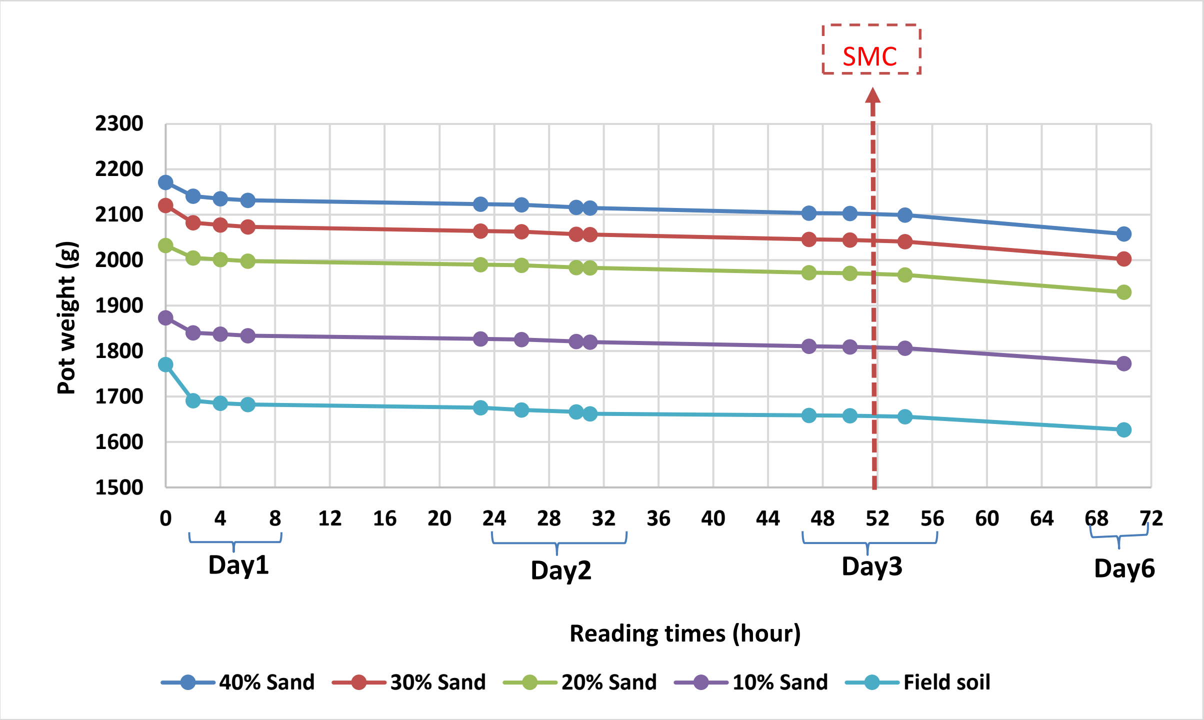


Figure 3.11. *Pot capacity for texture treatments A, B, C, D, E (Field soil, 10 %, 20 %, 30 % and 40 % sand respectively).*

- ***Irrigation treatments***

a) <u>Normal irrigation by re-watering up to field capacity (M1).</u>

The optimal soil moisture content for field lettuce has been reported to be field capacity with no evidence of growth limiting effect if soil moisture was kept periodically below field capacity, provided that intermittent irrigation that brings soil water content back to field capacity was applied (Gallardo *et al*., 1996). This treatment was intended to simulate the normal irrigation applied in the field uniformly regardless of in-field soil variation through watering all treatment to the measured FC for the main soil type. This allowed investigating how some areas in the field could be over or under irrigated when some different types of soil (zonal soil variation) in the field are not taken into account when planning conventional irrigation requirements

Estimating normal irrigation requirements was based on returning soil moisture back to field capacity, by calculating the loss in weight due to plant uptake over time. Therefore, the following weights were accounted for were (1) the average pot weight at field capacity was 1625.4 g, (2) The current weight of the pot (at the time of irrigation) was averaged between six pots of treatment A (to simulated conventional irrigation) each time, (3) the starting weight of the transplants (biomass + peat block) when they were planted; both were recorded individually at the beginning to be used in estimating the accumulation of plant growth at every irrigation, (4) The current biomass; three young plants were cut off at the soil surface and weighed at each irrigation incident to estimate plant growth between irrigations as follows: The accumulation in plant growth was calculated by subtracting the starting biomass weight from current biomass weight (measured at the time of irrigation).

Average starting weight of transplant (biomass + peat block) = 46.92 g
Average starting weight of the transplant biomass = 0.75 g
Average pot weight at FC = 1625.4 g

The formula used for irrigation requirement was; Irrigation need = Total pot weight at FC – {Current pot weight - (The accumulation in plant growth + The starting weight of transplants)}.

b) *Over irrigation (M2)*

This treatment was intended to examine whether, in scenarios of over-irrigation (i.e. rainfall after irrigation, wet zone that has lower water requirements than the rest of the field due to higher water table or poorer drainage conditions, etc.), whether soils with higher sand content could differ in crop establishment to soil of higher OM and less sand. Over-irrigation was done by watering the pots up to {FC + 20% of FC}

- ***Treatment applications***

Transplants, that were provided by commercial propagators (Second Willow Nursery, G's Growers Ltd, Cambridgshire), were planted inside the glasshouse 30/07/2015 one transplant per pot after irrigating the soil till saturation to simulate the planting process in the field. Extra transplants were also grown the same way to estimate the accumulation in the biomass production. Irrigation was carried out every three days where the calculations were repeated at every irrigation event. Water was added using measuring cylinder and syringe. The extra 20% of field capacity was added after a period of six hours from the application of normal irrigation, to allow the soil (in irrigation treatment 2) to absorb the first supply of water and avoid losing the extra added water immediately by direct drainage from the bottom of the pots. Plants were harvested 14 days after planting by cutting plants off at the soil surface and then they were weighed.

3.1.2.2 Statistical analysis

Data were analysed by carrying out Dose Response analysis in GenStat (Payne *et al.*, 2009). Bar charts of soil moisture content at field capacity and standard errors bars for the means were presented for descriptive comparison between treatments.

3.1.2.3 Results

Irrigation treatment had no effect on plant fresh weight. There was no significant difference in fresh weight between the two irrigation treatments. Whereas, the sand had significant effect on the fresh weight, 16.3 % of the total variance was accounted for by the sand treatment (the added sand rate) {(s.s for the added sand-rate / s.s for the total variance) * 100 = (187.701 / 1153.987) * 100 = 16.3}. And 85 % of the variance accounted for by sand, fitted a straight line (a slope) that was significantly varied from 0 {s.s for Lin / s.s for the added sand rate) *100} = {(160.138 /187.701) * 100 = 85 % (Table 3.3 and Figure 3.12).

Table 3.3. Dose response analysis of variance results for the experiment GH2, where the variate is FW, d.f is degrees of freedom, s.s is sum of squares.

Source of variation	d.f.	s.s.	v.r.	F pr.
Added sand rate	4	**187.701**	9.42	<.001
Lin	1	**160.138**	32.13	<.001
Quad	1	19.377	3.89	0.050
Deviations	2	8.186	0.82	0.441
Residual	194	966.788		
Total variance	**198**	**1153.987**		

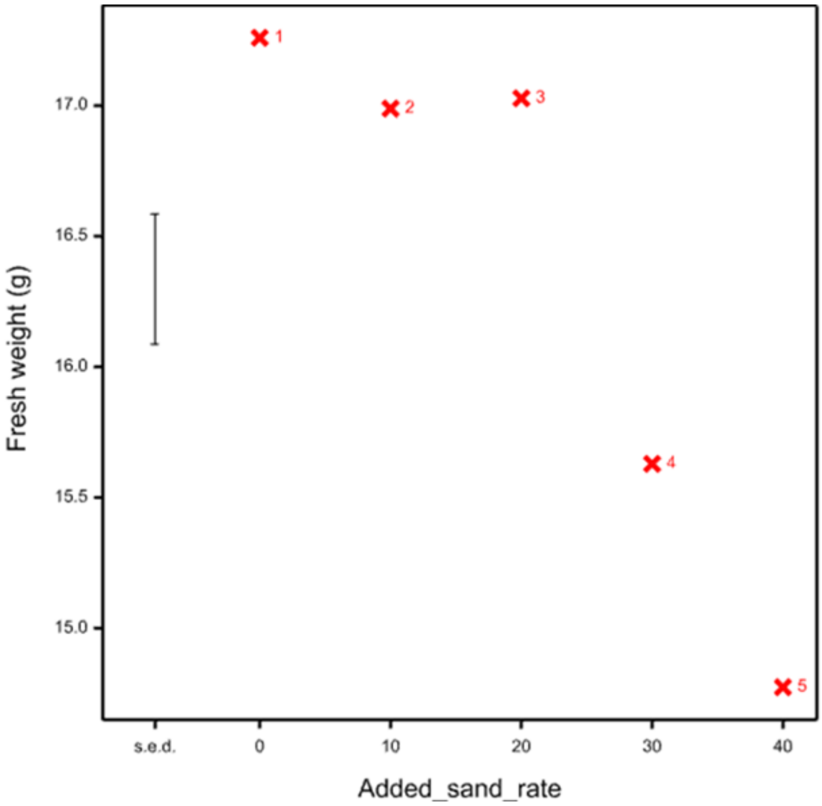


Figure 3.12. Means for the added sand rate as a percentage against the fresh weight of the plants (g /plant) 14 days after planting, for n = 20.

There was strong negative correlation between fresh weight (g / plant) at the end of the experiment and added sand rate (R = 0.7) and 84 % of the variance was accounted for by the sand treatments (R^2 = 0.84) (Figure 3.13).

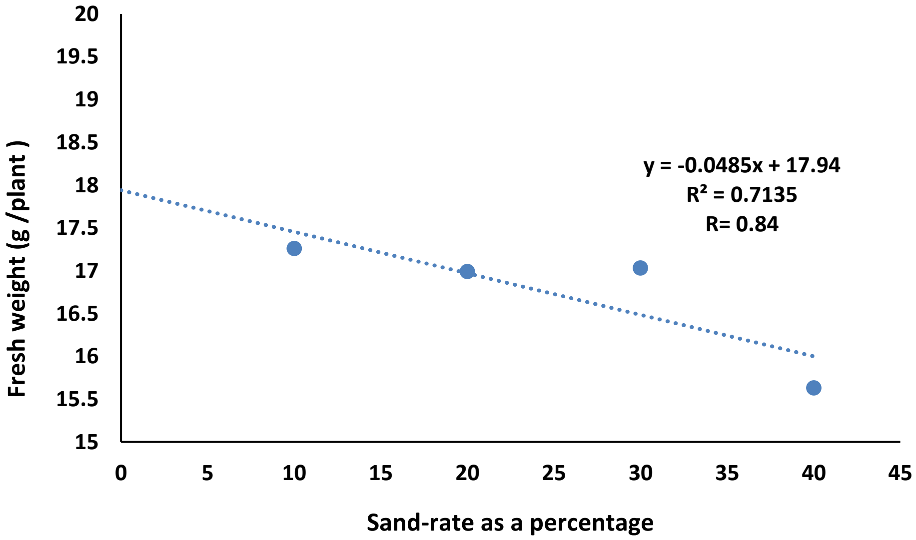


Figure 3.13. The relationship between the percentage of added sand on lettuce growth at early stages of planting estimated as biomass weight g / plant.

There also was a strong correlation between soil moisture content at pot capacity and the added sand rate (R = 0.9) and 83 % of the variance was accounted for by the sand treatments (R^2 = 0.83) (Figure 3.14).

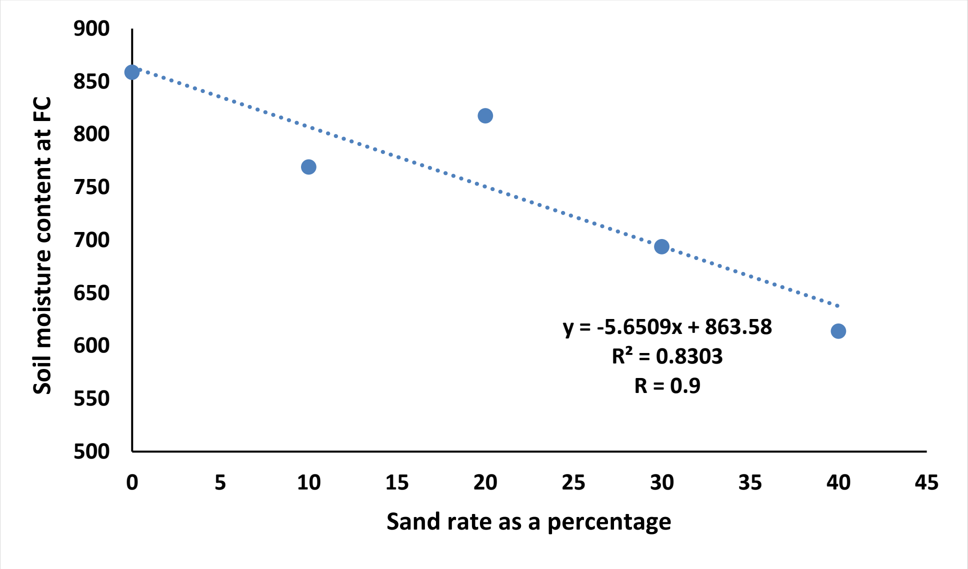


Figure 3.14. The relationship between the percentage of added sand on Soil moisture content at pot capacity for the five texture treatments.

3.1.2.4 Discussion:

Irrigation treatment had no effect on plant fresh weight. There was no significant difference in fresh weight between the two irrigation treatments. This could be partially explained by (Gallardo *et al*., 1996) study findings, which reported that lettuce was not sensitive to increased irrigation at around 24 days after planting from seeds (which coincide to the first week of the experiment GH2). Meanwhile Gallardo *et al*., (1996) found that the period in which lettuce was particularly sensitive to the irrigation was the last three weeks before harvest which was not covered in this experiment. Sand percentage affected the water holding capacity of the soil, which supports the suggestion that soil moisture retention is affected by the varying sand percentage in soil across the field, as expected. This highlighted the importance of moisture sensor locations in the field which are commonly used by growers to schedule irrigation requirements. That is because, when soil texture and organic matter content vary, soil moisture and water holding capacity will vary. The positive effect for the sand in Redmere P57 in FT3 is suggested therefore to be linked to sand benefits in waterlogging conditions or poor drainage.

There was strong negative correlation between the attained fresh weight (g / plant) 14 days after transplanting and added sand rate (R = 0.7) where 84 % of the variance was accounted for by the sand treatments (R^2 = 0.84). However, since the drained solution was not tested, and no test was done to the nutrient contents in the substrate, it cannot be confirmed whether the reduction in growth is due to reduction of the available water exclusively or also due to the dilution of the nutrients.

3.1.2.5 Conclusions:

- Variable sand contents in the soil Sand percentage result in variable soil moisture retention and availability.
- The attained fresh weight (g / plant) 14 days after transplanting correlated strongly and negatively with the added sand rate (R = 0.7) where 84 % of the variance was accounted for by the sand treatments ($R^2 = 0.84$).

3.1.2.6 Limitations:

- Significantly different irrigation treatments were not achieved probably due to the small size of the pots which was drained rapidly.
- The drained solution was not analysed, whilst it could have added more information to explain the growth difference between treatments.

4 Chapter 4: Lettuce variation at early stages of growth: during transplant propagation and at transplanting

4.1 Introduction

The rise of transplanting systems has mitigated the problem of seedling failure and improved the final yield (Grey, 1986) to a great extent, and improved the predictability of the maturity and harvest time overcoming the problem of predicting seed emergence (Wurr *et al*., 1984). Nevertheless, variation in the sizes of lettuce transplant appear to have a considerable influence on the variation of the final crop yield. Why, where and how this variation occur, has not been clearly identified or agreed on yet. Harwood *et al*., (2010) argued that systematic change of crop development across the field due to soil and microclimate variability is only “superimposed” on the variation caused by the plants themselves and described it as “inherited” plant to plant dissimilarity. Their experimental work included a number of growers that participated in both transplant and field trials to establish the extent to which yield variation at harvest was accounted for by the variability amongst transplants. However, there was limited data defining the state of soil or transplants state of uniformity at planting, and the study relied mainly on comparing the coefficient of variation at early stages of growth to the coefficient of variation at harvest. Harwood *et al*., (2010) suggested that head weight variability at harvest resulted mainly from the inherent plant to plant variation. This variation was generated early in the transplant stage and accounts for most of the final yield variation in the yield rather than field conditions. In 2013, Kerbiriou *et al*. (2013a; 2013b) carried out a number of glasshouse and field studies, to investigate the variability of transplant size on the lettuce biomass and rooting systems, as well as, to investigate the performance of both roots and shoots under limiting supplies of water and nitrogen, and showed that by planting lettuce transplants of different sizes, the small sized transplants mostly resulted in delayed growth, development and maturity compared to larger transplants.

Variability in lettuce transplants is not only concerned with seed emergence or the above ground shoot, but also concerned with the rooting system. Johnson *et al*., 2000 studied genetically and phenotypically the root architecture and soil exploitation in cultivated lettuce (*Lactuca Sativa L.*) and compared it with its wild relatives (*Lactuca Serriola L.*) and found that root proliferation has preferential distribution in the soil zones that have greater nutrient concentrations or available water which improves the plant’s ability to access sources in non-uniform soils. However, the study also concluded that selection and breeding for plants with greater root biomass have negative impact on the yield (Johnson *et al*., 2000). Modern lettuce cultivars (*Lactuca sativa* L.) have shallower and smaller root systems in comparison with their wild relatives, as they have been bred for producing uniform vegetative growth and high yields under high input cropping systems (Johnson *et al*., 2000; Gallardo *et al*., 1996). This makes them underperform in soils where resources are limited and when spatial and temporal variabilities occur in the available resources; the smaller root systems for these cultivars make the plants unable to extract nutrients and moisture efficiently in the deeper and the surrounding zones of the soil profile (Johnson *et al*., 2000; Kerbiriou *et al*., 2013). This in turn, makes exposing Lettuce young plants and propagated transplants to early stress more harmful than exposing them to stress later on during their production cycle (Kerbiriou *et al*., 2013b). Therefore, Iceberg lettuce transplants are produced commercially under uniform and controlled conditions in order to produce a more robust and uniform young plant that can establish better under field conditions. Growers aim to transplant the lettuce uniformly in the field at regular spacing and depth to ensure even and sufficient accessibility of the transplants to resources of moisture, nutrients and light. There is a very limited research material however, on the effect of placement and positioning of lettuce transplants in the soil on the growth and development of this crop.

The variability in soil nutrients, moisture and soil texture creates variability in the conditions of growth and development for plants (Gallardo *et al*., 1996; Johnson *et al*., 2000; Corwin *et al*., 2003; Kerbiriou *et al*., 2013a and 2013b; Stadler *et al*., 2015). These conditions are particularly important at early growth and establishment of the crop life cycle where the plants are still young and vulnerable (Wurr and Fellows, 1984; Costigan, 1984; Costigan, 1986; Wurr *et al*., 1987; Johnson *et al*., 2000; Kerbiriou *et al*., 2013a and 2013b). In cases of consistent growing media (when the growing media is uniform or homogenous), variable placing of transplants in the field (such as planting depth, direction and spacing) may result in variable orientations of these plants. The growing plants will respond to the surrounding resources or factors (light, moisture, nutrients, obstacles, etc.) and the response will vary with the plant postion, which is mostly a type of plant movement (phototropism, gravitropism, hydrotropism, thermotropism, thigmotropism; plant movement in response to physical contact, Traumatropism; plant movement in response to injury, etc) (Molas and Kiss, 2009, Hopkins and Hunter, 2009 and Darwin, 1897). Although the mechanisms of these movements could be still arguable in research, cited researchers have agreed on plants changing in morphology, development or direction of growth in response to external stimulants. And placement of small plants variably in the soil, creates variability in the exposure of these plants to the surrounding stimulants and hence, variable responses. Furthermore, the size of the area of contact between the block and the surrounding soil adds onto the variability in green shoot placement. This variability in peat block contact with soil creates dissimilarity in the degree and the strength of contact with the root and hence, the establishment of the rooting system as an additional source of variation.

In this chapter, plant to plant variability was investigated before and at the transplanting stage and then followed to examine the effect of this variability on lettuce growth and development. The chapter also investigates the effects of variable planting depth and placement of the propagated transplants in the field on the final yield. The questions this chapter is aiming to answer is:

1) How variable is lettuce transplant size within the propagated trays?
2) Does this variability follow a certain pattern?
3) Does this variability continue to the field?
4) Does variable planting / placements in the field result in variability in the marketable lettuce heads?

4.1.1 Experiments T1a (Preliminary) and T1: In-tray transplants variation

Hypothesis

- Transplants from genetically uniform seeds vary in development (weight) within the same propagated tray and this variability is dependent on their location within the tray (edge versus centre).

4.1.1.1 Materials and methods

- **Commercial production of lettuce transplants at Second Willow Farm.**

Lettuce seeds were planted automatically into trays of peat blocks, with one seed placed in each block. Each tray contained 11 rows of 16 peat-blocks = 176 blocks of transplants in total. The block size was 3.8 x 3.8 X 3.8 cm. The seeds were germinated in a temperature-controlled room at 16°C and high humidity (90 %) from day zero to day three followed by 17 days of propagation in a glasshouse compartment at approximately 18°C. At 20 days old, the transplants were moved to the final compartment of the glasshouse before field stages, where the trays for this experiment were selected; the trays were selected from the same germination patch from the same location in the centre of the compartment away from shading and doors. The trays were irrigated throughout glasshouse growth following standard commercial practice, receiving approximately 800 ml water / tray per day.

- **Experiment T1a**

Four trays of lettuce transplants (*Lactuca sativa cv. Soleison cru)* (each containing 176 transplants) commercially produced by Second Willow Nursery, G’s Growers Ltd, Cambridgeshire, UK were used for this experiment. The trays studied were transported to Harper Adams University 20 days after seeding and were assessed 23 days after seeding. The plants were held for two days in the glasshouse at HAU at set conditions of 15° C (day temperature) and relative humidity 65 %. All the transplants were destructively measured by removing the top growth at the surface of the peat block with scissors and weighed for each individual plant using digital balance (FZ-i model, A & D Company Limited, Oxfordshire, UK). The trays were irrigated during these two days by watering can to keep the blocks moist. The location of each transplant within the tray was recorded.

- **Meanwhile, Experiment T1**

This experiment was carried out on twelve trays of lettuce (*Lactuca sativa cv. Soleison cru)* transplants commercially produced by Second Willow Nursery, G's Growers Ltd, Cambridgeshire, UK. The trays sampled were planted on 06/05/2016 and were sampled at 20, 21 and 22 days after seeding with 3 trays, 5 trays and 4 trays sampled each date respectively, starting from 25/05/2016. The number of trays was not balanced between dates due to time restrictions as the experiment started from midday on Day 1 and lasted until early afternoon Day 3. During these three days, only one measured tray was taken out of the glasshouse at a time, while the rest of the trays remained in the same location and continued to receive the same conditions. The transplants were destructively measured *in-situ* over three successive days as described above.

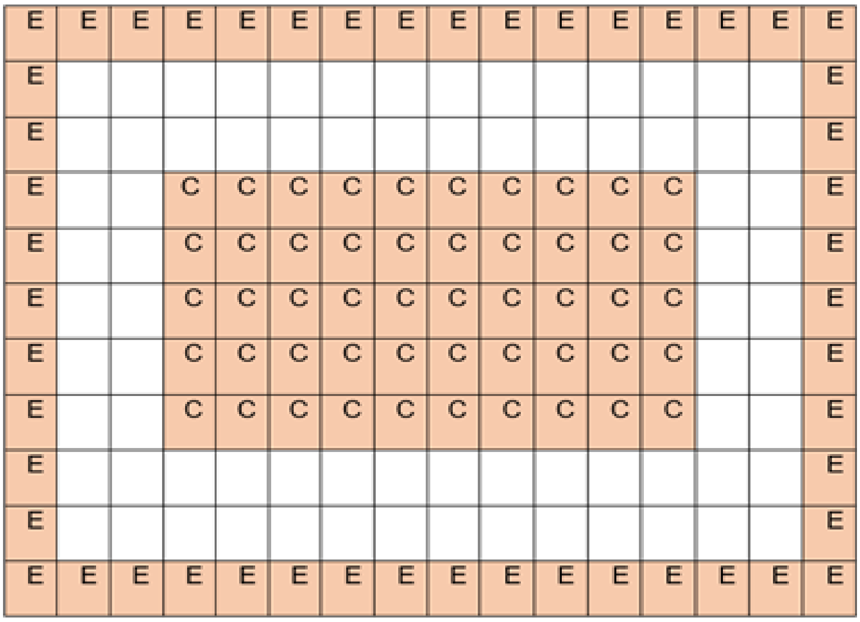
4.1.1.2 Data analysis

- **Experiment T1a:**

The coefficient of variation (CV) for each tray of plant weights was calculated manually in MS Excel as CV = ((standard deviation ÷ the mean) x 100), the mean, the minimum and the maximum values were calculated for each tray individually (n = 176).

- **Experiment T1:**

The data were presented using 3D surface charts, generated using MS Excel, to display the trends in fresh weight values across the two dimensions of the tray. The CV was calculated as described above. In addition, the fresh weights of the edge plants were compared to the fresh weights of the centre plants using the Two-sample T-test in GenStat 17th Edition (Payne, 2009). Two equal populations of transplants were selected; 50 from the edge (E) and 50 from the centre (C) of each tray as shown in Figure 4.1. This was done for each of the 12 trays.



E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
E															E
E															E
E			C	C	C	C	C	C	C	C	C	C			E
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Figure 4.1. Tray layout showing two equal populations of transplants from the edge (50 E) and from the centre (50 C) used in a T-test to compare the edge to the centre.

Additionally, the data from all days and all trays was grouped and a t-test (paired two samples for means) was performed to compare the edge to the centre means of all the data for n=12.

4.1.1.3 Results

- **Experiment T1a**

The preliminary study T1a showed that there was a large variation in the weights of transplants that were propagated together within the same tray and of the same batch of transplants (plants that were seeded on the same day and germinated and grown under the same conditions within the same compartment of the glasshouse and germination room). The mean fresh weight for the transplants per tray ranged between 2.2 and 2.5 g / plant (Table 4.1). Within the trays there was a wide range of plant biomass with the smallest plant being observed in tray 1 (0.22 g) and the largest plant in tray 3 (4.38 g). The CV varied between trays with a range between 24 % in tray 2 to 33 % in tray 1 (Table 4.1).

Table 4.1. Means of plant fresh weights per tray, minimum, maximum and coefficient of variation (CV) values for each tray

Tray	CV %	Mean g/plant	Minimum g/plant	Maximum g/plant	Present cells count	Standard Deviation	Standard Error
1	33	2.5	0.22	4.22	172	0.8	0.06
2	24	2.3	0.64	3.69	176	0.5	0.04
3	27	2.5	0.78	4.38	176	0.7	0.05
4	25	2.2	0.58	3.91	176	0.6	0.04

- **Experiment T1**

Within-tray variability and the change in the fresh weight of the transplants:

The CV for the 20 days old transplants (20 DOT) was 25.3 %, indicating a large variation in the fresh weights of the transplant top growth (Fowler, 1998). Fresh weight increased over the three days increasing from 0.76 g to 1.17 g (Table 4.2). Although the CV decreased from 25.3 on Day 1 to 21.4 % on Day 3, it remained relatively high for all the trays. Indicating a considerable level of variability in the measured trays.

Table 4.2 Mean transplant biomass per tray and CV across the three sampling dates, Experiment T1.

	Sampling date (days after seeding)		
	Day 20 (n=3)	Day 21 (n=5)	Day 22 (n=4)
Mean transplant biomass per tray (g/plant)	0.76	0.93	1.17
Mean CV per tray (%)	25	23	21

Comparison of transplants fresh weight between the edge and the centre:

The mean weight of the centre plants was greater than the edge plants at each date. However, the differences were not significant (*P* > *0.05*) at any tray or date (Table 2). The mean weight of edge plants was 0.9 g / plant, whereas the centre plants had a mean weight of 1.0 g / plant. Mean values, differences and degree of significance are presented in Table 4.3.

Table 4.3. The difference in means of transplant weights between the edge and the centre of the tray (g/plant) averaged between 50 transplants (n=50).

	Tray	Edge	Centre	Difference	Significance
Day1	Tray1	0.72	0.78	0.06	N
	Tray2	0.73	0.82	0.10	N
	Tray3	0.70	0.82	0.12	N
Day2	Tray1	0.93	1.11	0.18	N
	Tray2	0.80	0.99	0.19	N
	Tray3	0.79	0.89	0.10	N
	Tray4	0.89	0.96	0.07	N
	Tray5	0.90	1.05	0.15	N
Day3	Tray1	1.10	1.27	0.17	N
	Tray2	1.08	1.29	0.21	N
	Tray3	1.14	1.18	0.04	N
	Tray4	1.04	1.14	0.10	N

The paired t-test that was performed on edge vs. centre means from all trays and days showed no significant difference between the two variables.

Examining the spatial patterns of variability across the tray

The spatial pattern of fresh weight distribution was not consistent either across the trays or over time (over three days) (Figures 4.2, 4.3 and 4.4).

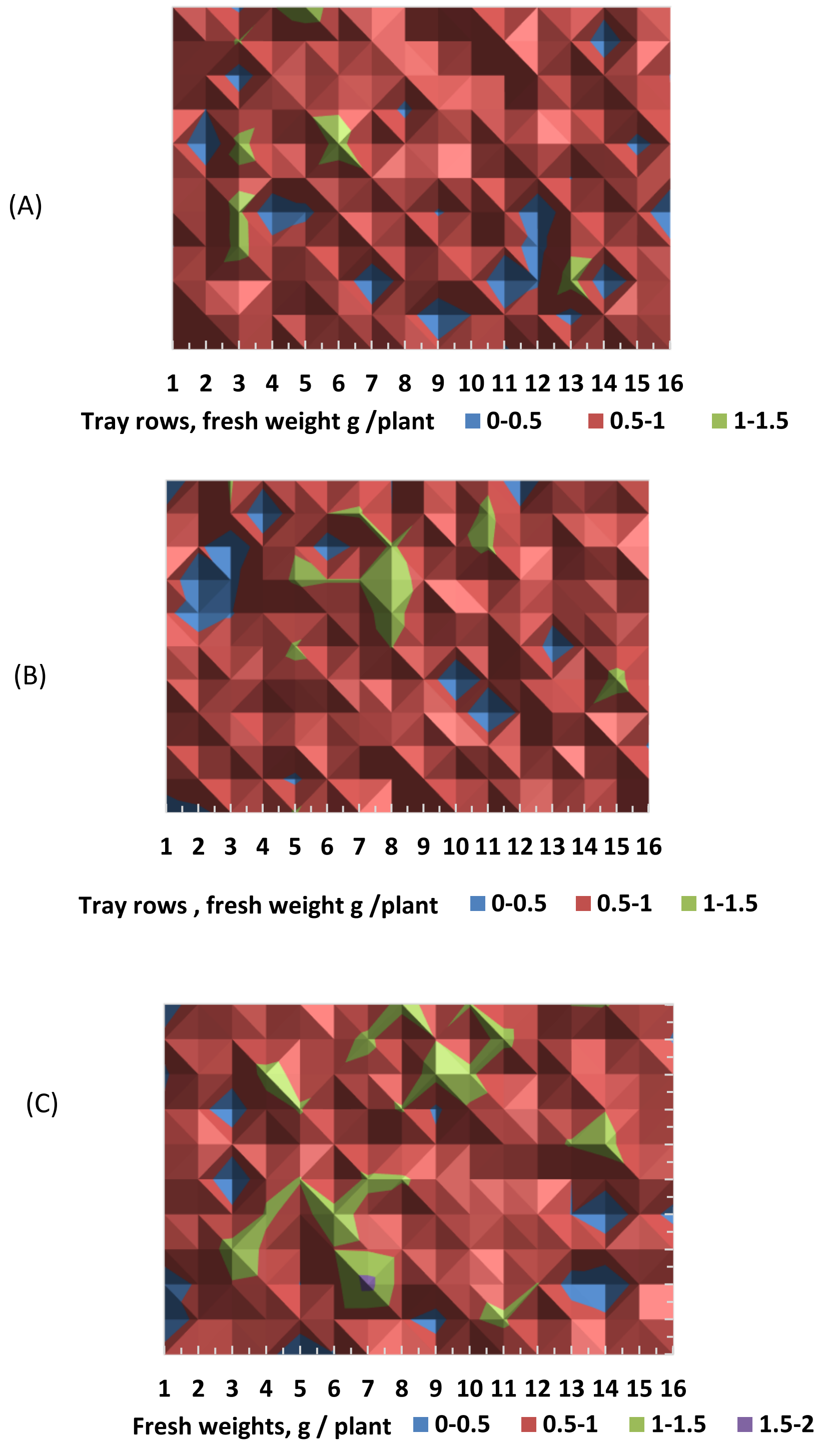
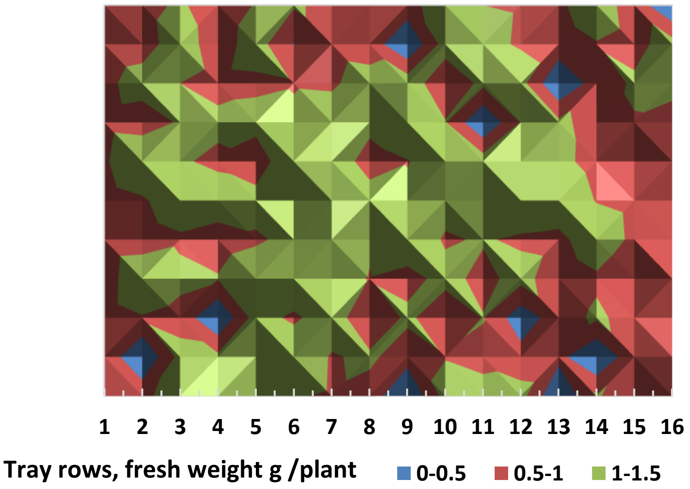
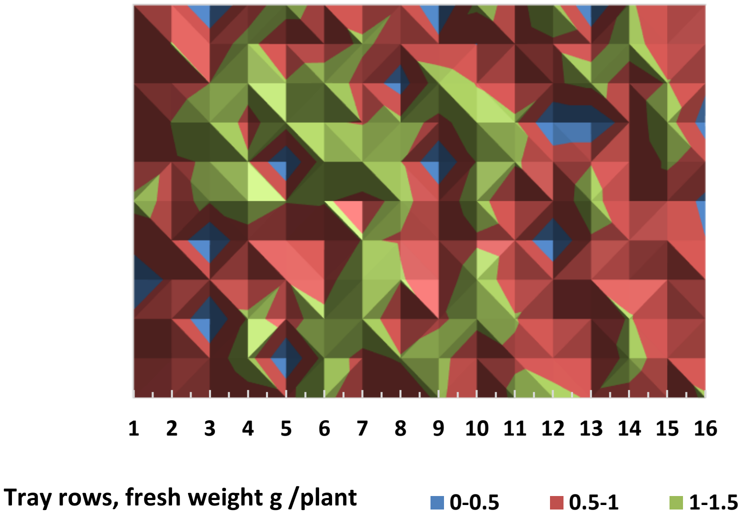


Figure 4.2. (A), (B) and (C) 3D surface charts for the three measured trays of 20 days old transplants. Different colour bands indicate different fresh weights data (g FW / plant) amongst transplants across the tray. Sampled on Day 1 of the experiment 25/06/2016 (n = 176.)

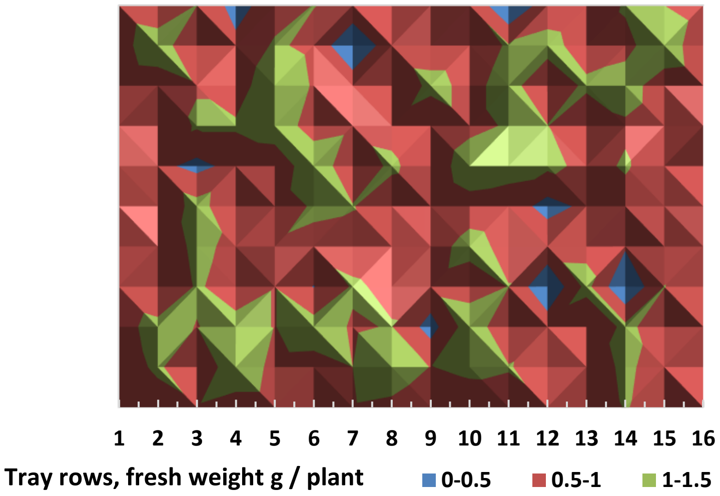
The CV for the 21 DOT and 22 DOT were 23.2 % and 21.4 % respectively, averaged amongst five trays of transplants for the 21 DOT and four trays of transplants for the 22 DOT. The latter two CV were also high (Fowler, 1998) indicating large variability amongst these (older) transplants.



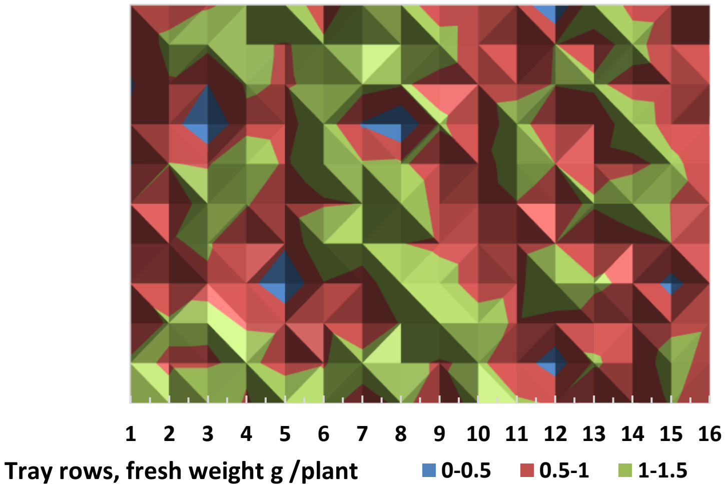
(A)



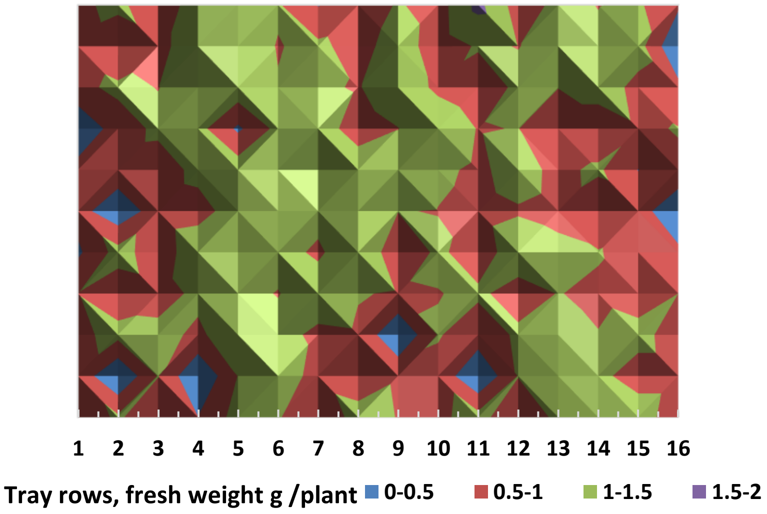
(B)



(C)



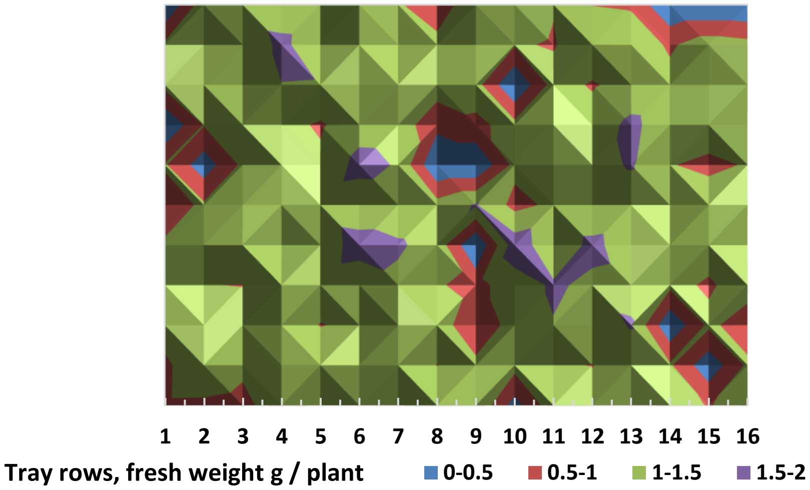
(D)



(E)

Figure 4.3. (A), (B), (C), (D) and (E), 3D surface charts for the five measured trays of 21 days old transplants. Different colour bands indicate different fresh weights data (g FW / plant) amongst transplants across the tray. Sampled on Day 2 of the experiment 26/06/2016 (n = 176.)

Comparing trays from Day1 with trays from Day 3 (Figure 4.2 and Figure 4.4), where the transplants have grown two more days. The variability remained although was distributed in smaller patches, with the majority of the transplants belonging to the 1 – 1.5 g group (band) (Figure 4.4. (A), (B), (C), and (D)) and larger transplanted in general (from 1 to 2 g) more blocks. However, there were still no certain spatial pattern to be identified.



(A)

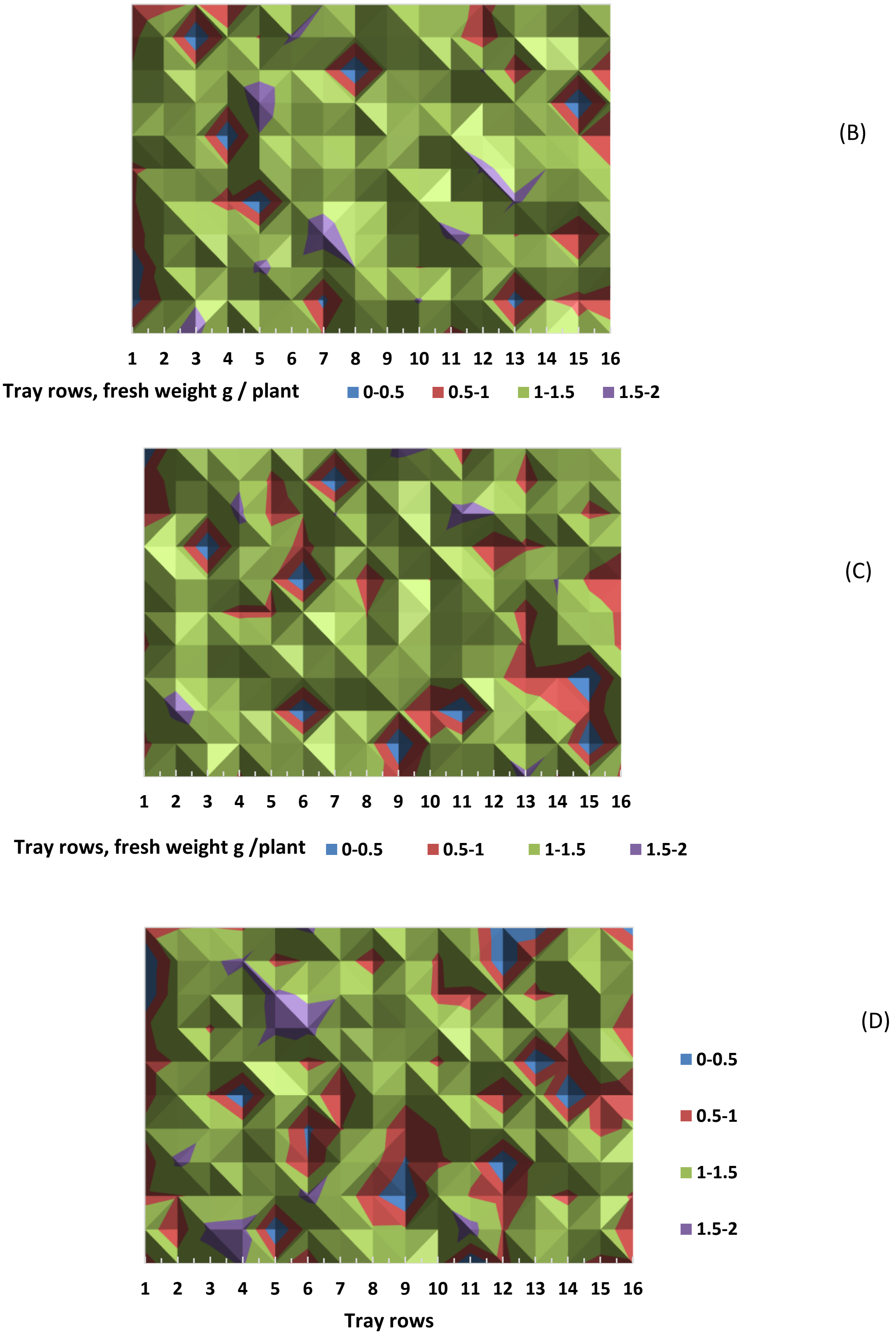


Figure 4.4. (A), (B), (C) and (D). 3D surface chart for the four trays tray of 22 days old transplants (g / plant). Different colour bands indicate different fresh weights data (g FW / plant) amongst transplants across the tray. Sampled on Day 3 of the experiment on 27/06/2016 (n = 176).

4.1.1.4 Experiments T1a and T1 Discussion:

The large CV values in Experiment T1a indicated a considerable amount of variation within transplants of the same tray that were grown from the same genetic material and propagated under the same conditions which required further investigation. Therefore, Experiment T1 was carried out, and all of the twelve trays that were examined in T1 on transplants aged 20, 21 and 22 days, showed similar results of high CV values.

This study showed that over 3 days of growth, the CV, although reducing, remained relatively high, indicating substantial variation amongst transplants. The increase in the mean plant biomass over the three-day period, was expected as the transplants were growing from Day 1 to Day 3 of sampling. Meanwhile, the decrease in the CV over the three days indicate that the variability is declining with age.

The variability in fresh weight amongst transplants can be partially explained by the inherited plant to plant variation as suggested by Harwood *et al*., (2010). Their study report suggested that natural variation is accounted for most of the variation in transplants. However, Harwood *et al*., (2010) overlooked the fact that in commercial production, the field could be planted by several batches of transplants that might differ in days or had undergone variable conditions during the process.

Although the mean values were always smaller on the edge than in the centre, there was no difference in fresh weights for transplants between the edge and the centre of trays so the hypothesis that transplants on the tray edge were smaller than the plants in the centre of the tray was not supported. However, the large value of CV necessitates investigating the reasons behind this variability and how could the micro-ambient conditions be used to affect this variation (e.g. peat block size, tray size, temperature and moisture distribution, shading from tray edges or glasshouse poles, etc.)

A limitation of this experiment was lack of data with regards to the difference in moisture, light, temperature or root biomass between the edge and the centre of the trays. There were also other measurements that would have added more information to this experiment such as measuring the shading within trays. It would be beneficial to compare trays from different locations of the glasshouse where there are differences in temperature and light conditions to understand the effect of these conditions on the degrees of variability within the trays.

The unbalanced number of trays measured between days and the small number of trays per day is another limitation of these two experiments as more replicates were needed to confirm the spatial pattern of variability that could also change with transplant growth over time. Or how would that change after the 3 days period that was covered with this experiment.

4.1.2 Experiment T2: The effect of transplant size difference on subsequent growth

4.1.2.1 Introduction to data

Experiments T1a and T1 showed a large variation in transplant development within the same propagated trays at the block stage. The weights of transplants of the same age ranged from 0.02 to 4.38 g / plant in the experiment T1a and from 0.08 to 1.79 g / plant in the experiment T1. This experiment (T2) aimed to investigate whether this particular type of difference in transplant growing within the same trays or the same patch will result in subsequent variation in growth and development after 14 days growth. Moreover, the 14 days period was targeted firstly to increase the length of observation in comparison with T1a and T1, and secondly because this is the time range that the grower reported being able from experience to predict yield variation, identifying visually the two weeks old plants (in the field - days after transplanting) that are expected display delay maturity or development in size at harvest time when the majority of the heads in the field are ready for harvest (Rob Parker, pers comm).

Hypothesis:

- Variability in size amongst transplants of the same age and that germinated under the same conditions increase 14 days after planting

4.1.2.2 Materials and Methods

- Transplant production

Five trays of lettuce (*Lactuca sativa cv. Soleison cru)* transplants commercially produced by Second Willow Nursery, G's Growers Ltd, Cambridgeshire, UK were used for this experiment. (Production process explained in T1 and T1a materials and methods). The transplants were sown on 29/06/2016 under the same propagation conditions. The trays were selected from the same compartment and the area inside the commercial glasshouse. The trays were delivered to HAU on 15/07/2016 and were held in a glasshouse at an average temperature 17° C and 63 % relative humidity conditions for three days before the experiment started.

- Establishing the relationship between the transplants sizes and weights

On 15/07/2016, a random group of 15 transplants (three from each tray) were destructively measured in terms of the length and weight for the purpose of establishing the relation between size and the weight. The transplants were cut using a sharp pair of scissors at the surface of the peat block. The whole fresh weight of the biomass was measured using a digital balance (FZ-i model, A & D Company Limited, Oxfordshire, UK) and the length was measured from the cut edge to the top of the oldest leaf of the biomass, using a ruler. The two measured parameters were plotted against each other to establish the relationship between leaf length and above ground plant biomass (Figure 4.5).

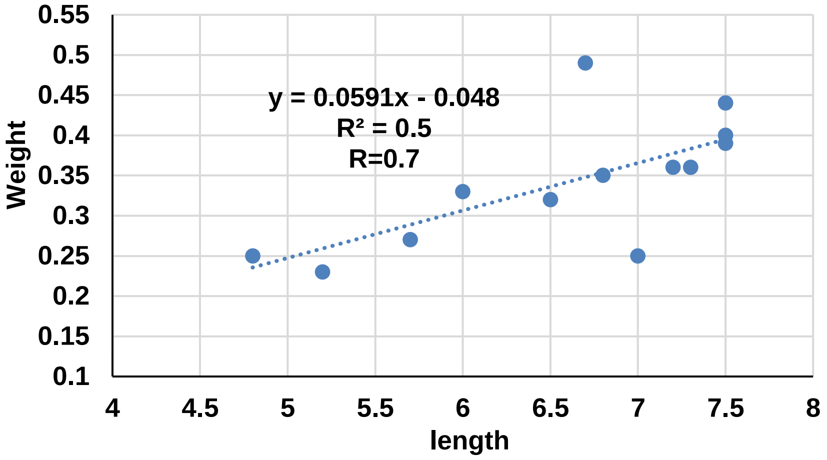


Figure 4.5. The relationship between the length of the transplant oldest leaf (cm) and the fresh weight of vegetative growth (FW) (g).

- Experimental design

The smallest and the largest transplants of lettuce across the five trays were selected visually (the largest 20 and the smallest 20 transplants from each tray = 40 per tray) to form two group sizes of transplants (small and large). Nine plants were selected from each size group (9 / 20 per tray) to create two treatments (small and large) making a total 9 x 5 = 45 replicates per size group (or treatment). The length of the largest leaf of each plant was measured and the starting weight estimated using the relationship established previously (Figure 4.5).

- Plant growth

Ninety plastic pots (Deep Rose pots 8 X 11 X 18cm; LBS Horticulture Ltd, Lancashire) were filled with John Innes No.2 (K G Loach, Cheshire, UK).

The pots were placed on the top of a bench in a glasshouse compartment at Harper Adams University. The average glasshouse temperature over the experiment time was 17 °C at night and 24 °C in the day with an average relative humidity was 73 % at night and 52 % in the day.

On 18/07/2016 the pots were irrigated slowly to saturation immediately before planting, one per pot. The pots were labelled and randomised using GenStat 17th edition. The transplants lengths were measured on the day of planting using a ruler to estimate their starting weight non-destructively, using the relation established in Figure 4.5.

- Irrigation

The pot capacity (PC) was established following the protocol described previously (Glasshouse Experiment GH2 -section 3.1.2.1- establishing field capacity). Soil moisture content (SMC) at PC was calculated as follows;

SMC = (Soil wet weight – soil dry weight) / (soil dry weight)

Estimating the irrigation requirements was based on returning soil moisture back to PC, by calculating the loss in weight due to plant uptake over time. This was calculated by subtracting current pot weight (at the time of irrigation) as averaged between four pots (two pots of each treatment) from the average pot weight at pot capacity. Plant biomass accumulation in this experiment was dropped from irrigation calculation to avoid complexity. Irrigation was carried out every 3 days and the calculations were repeated at every irrigation event. The water was added using a measuring cylinder and a syringe.

- Measurements

The plants were grown for 14 days and harvested by cutting at soil surface using a sharp pair of scissors. Each cut transplant was weighed as described previously. Data were analysed using the Two-Sample T-test in GenStat 17th edition.

4.1.2.3 Statistical analysis:

All pairs of groups were compared using two-sample T-test in Genstat17th Edition (Payne, 2009).

4.1.2.4 Results:

The pot weight average at PC was 855 g at 53.8 % soil moisture content. The correlation equation between transplant weights and lengths for the destructively measured subsample enabled estimating the starting weight of transplants non-destructively. The mean difference in length between the small and the large group of transplants was 2.69 cm (Figure 4.6).

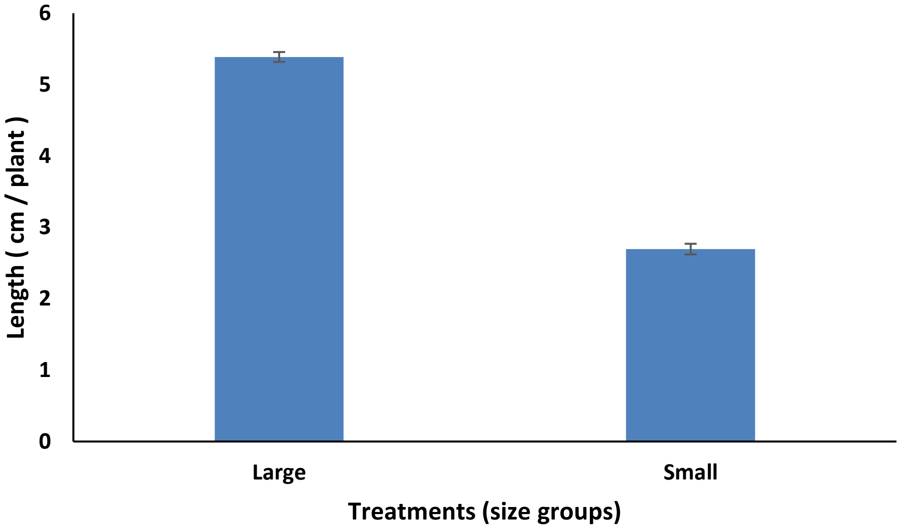


Figure 4.6. The starting difference in length (cm / plant) between the two size groups of transplants (small and large). The blue bars show the mean lengths for n = 45 and the error bars show the standard errors of the samples.

The derived starting weights of the studied transplants showed an average difference of 0.2 g / plant (Figure 4.7)

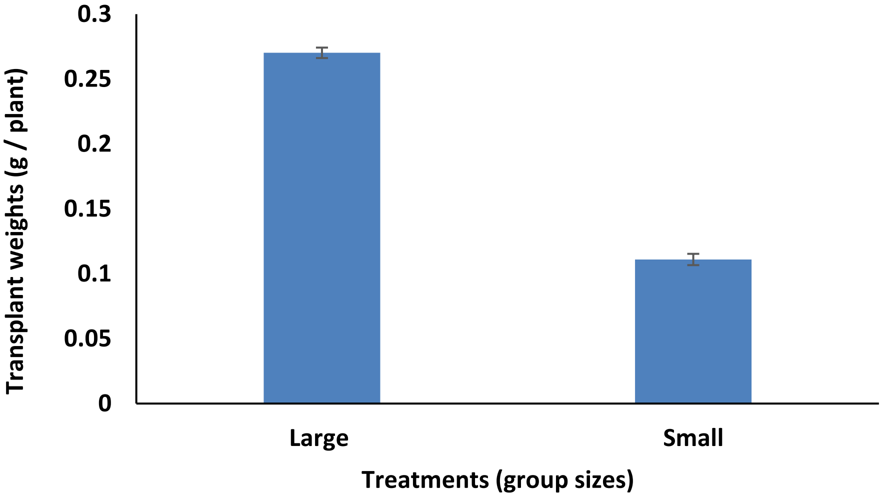


Figure 4.7. The difference in the starting fresh weight between the large and small size groups of transplants as estimated for n=45. Blue bars show the means and the error bars show the standard errors of the samples.

The small group differed significantly from the large group of transplants at the start of the experiment in both weights and lengths ($P < 0.001$). There was no effect for the trays on the transplants sizes or weights. When the young plants were harvested 14 days after planting in separate pots, the two size groups also differed significantly in weights with (P

< 0.001). The weight difference was on average 13 g / plant between the two groups (Figure 4.8).

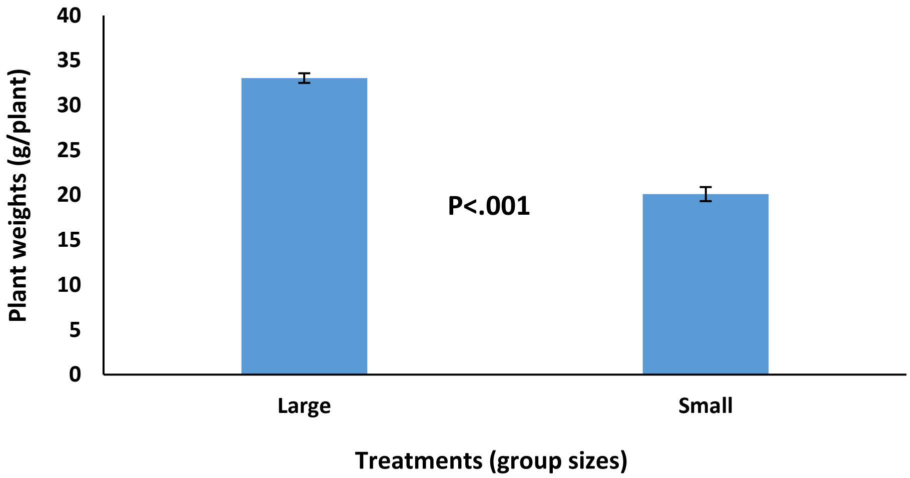


Figure 4.8. The difference in fresh weight between the large and small group-size of transplants as measured (weighed) 14 days after planting (n=45). Error bars show the standard error of the samples

The difference in weight between the two group sizes was larger than the difference in weight between the two group sizes at the start of the experiment suggesting an amplification in the difference over time. The trays had no effects on the sizes or the weights of the transplants at either stage of the experiment.

The ranges of the values and the averages of all groups are demonstrated in Table 4.4.

Table 4.4 The ranges and the average values of the estimated starting lengths and weights of transplants for each of the small and the large group sizes (n=45), the measured weights and lengths 14 days after planting for (n=45)

	Range	Average
Starting Length (Small) cm	1.8 - 3.4	2.7
Starting Length (Large) cm	4.7 - 6.4	5.4
Estimated starting weight (Small) g	0.1 - 0.2	0.1
Estimated starting weight (Large) g	0.2 - 3	0.3
Weight 14 DAP* (Small) g	4.9 - 28.5	20.1
Weight 14 DAP (Large) g	23.4 - 39.2	33.029

*DAP: Days After Planting

4.1.2.5 Experiment T2 Discussion:

There was a significant difference in the estimated starting fresh weight between the small and the large transplants ($P < 0.001$). This response was consistent between trays. This variability cannot be simply explained by the reasons suggested by Wurr *et al*., 1987 and Wurr and Fellow 1991, as both studies suggested that the main causes of variation between transplants are age, temperature, solar radiation (Wurr reported that 98 % of the differences the growth of lettuce plants after seed emergence were accounted for by temperature). The transplants in experiment T2 were sourced from the same batch and the same location in the glasshouse where they had undergone (relatively) the same environmental conditions and held for the time of the experiment under relatively uniformly controlled environment. The difference between the small and the large group of transplants supports more the explanation provided by Harwood *et al*., 2010 stating that it is mainly inherited plant to plant variation. However, with the limitated data available about the exact seed emergence date in Harwood *et al*., 2010, study and information about the uniformity of the propagation or field conditions, this study suggests that there could be an effect to the precise emergence time of the seeds and the micro climate within the glasshouse or trays.

Similar results were found by the end of the experiment (14 days after transplanting) where significant difference was found in the fresh weight between the small and the large group of transplants ($P < 0.001$). The resulting figures suggest that 0.1 g / plant average difference in the starting weight between the small and the large group of transplants multiplied into an average difference 20 g / plant after 14 days of growth. This supports the findings of Costigan and McBurney's, (1983) and Kerbiriou *et al*., (2013) about the importance of initial growth as the established difference in dry matter building and size development has been shown to persist to harvest (Costigan and McBurney's, 1983 and Kerbiriou *et al*., 2013), although this experiment ended before the plants reached commercial maturity. which contradicts to some extent with both Wurr *et al*., (1987) and Wurr and Fellow (1991) who suggested that variability in the final yield in the field is a mainly combination of both the growth stage of transplants and the ambient conditions.

4.1.3 Experiment T3a and T3: The effect of variable in-soil placement of transplants on growth and yield

Introduction to data collection

In a field scouting visit during planting time, it was observed in the field that some transplants had been placed in irregular positions at planting (Figure 4.9). Consequently, a preliminary glasshouse study (T3a) was designed to test the growth of transplants for 14 days after they were planted in variable positions (placements) in separate pots.

Figure 4.9. Left; a transplant with lack of contact with the soil in a rough soil bed. Right; a transplant over-covered with soil.

4.1.3.1 Experiment T3a; A preliminary study

4.1.3.1.1 Hypothesis

Variable placement of transplants in the soil results in variation in growth and development 14 days after planting.

4.1.3.1.2 Materials and methods

Forty-four pots size (18 x 10 x 11 cm) were filled to the same level with field soil from Zone C (which was used for GH2). Transplants of Iceberg lettuce (*Lactuca sativa cv. Soleison cru)* were sourced from G's propagators (For propagation conditions see section 4.1.1.1.). Transplants that had relatively similar sizes and shapes were selected for this experiment from the same tray and they were planted in 4 different positions each to represent a placement treatment (4 treatments) and each treatment had 11 replicates (Table 4.5 and Figure 4.10) The glasshouse temperature over the experiment time was 16.8 °C at night and 23.6 °C during the day as an average. And the average of relative humidity was 74.1 % at night and 54.1 % in the day. Pots were irrigated through capillary matting and plants were harvested 14 days after planting and weighed.

Table 4.5. The transplant positioning treatments

Treatment	Description
Standard (S)	Transplant placed with half the block under the substrate surface, half the block above the surface.
Under (U)	Transplant block placed under the surface with 2 cm substrate above the top of the block.
Above (A)	Transplant block placed on the surface of the substrate.
Tilted (T)	Transplant placed with half the block under the substrate surface, half the block above the surface. Block oriented at a 45° angle to the substrate surface.

Figure 4.10. Four pots representing the three transplants positioning treatments

All the plants were harvested on day 14 after planting using a sharp knife and by cutting all the leaves off at the surface of the block. The plants were weighed fresh (g FW plant^{-1}) using a digital balance (FZ-i model, A & D Company Limited, Oxfordshire, UK) and the weight recorded.

4.1.3.1.3 Results

Plant growth was similar for the four treatments (Figure 4.11). The mean leaf fresh weight of the standard treatment was 11.1 g. The transplants that were planted under the surface of soil had the lowest mean fresh weight and the tilted treatment had the highest (Table 4.6), Figure 4.11. However, the difference between the treatments was not statistically significant (P = 0.338).

Table 4.6. Fresh weight of the leaves after 14 days (n=11) (P = 0.3).

Treatment	W (g / plant) (
Standard	11.1
Under	10.8
Above	11.1
Tilted	12.3
Mean	11.33
SE	0.04
LSD	1.8

Figure 4.11. Plant growth 14 days after planting at the end of the experiment.

4.1.3.2 Experiment T3: The effect of transplant variable placement in the field up until maturity:

4.1.3.2.1 Introduction to data

The preliminary study T3 was modified and transferred to the field as a new experiment (T3) to allow more replicates and to examine the effect of variable transplanting positions under field conditions and commercial production practices. This experiment examined the response of growth at maturity to transplant placement in the field under commercial growing conditions.

4.1.3.2.2 Hypothesis:

Variable placement of transplants in the soil results in variation in lettuce head yield and quality at harvest.

4.1.3.2.3 Materials and methods

The four treatments studied in T3 were used in addition to a fifth treatment which was the “Side” treatment, where the transplants were placed on the side of the block on the soil surface and only one side of the peat block was in contact with the soil. The treatments in T4 were as follow:

Treatment	**Description**
Normal (Standard)	Transplant placed with half the block under the substrate surface, half the block above the surface.
Side	Transplant block laid on the side on the substrate surface. Block oriented at a 90° angle to the substrate surface.
Above	Transplant block placed on the surface of the substrate.
Tilted	Transplant placed with half the block under the substrate surface, half the block above the surface. Block oriented at a 45° angle to the substrate surface.
Under	Transplant block placed under the surface with ~ 2 cm substrate above the top of the block.

- ***Site specifications and soil conditions***

Six plots of iceberg lettuce transplants (*Lactuca sativa* cv. *Soleison cru*) were established along with a commercial lettuce planting on 10/08/2016 in “Kenny Hill 44” field at G’s farm, Ely, Cambridgeshire (grid reference TL 6680/3505). The trial plots received the all commercial inputs as applied to the rest of the crop. Experimental plot locations within the field were chosen in homogeneous zones as identified from the grower experience as EC scans were not available for this field. Soil samples were taken from each trial block at harvest for analysis. Two soil samples were taken from two depths of each of the trial blocks; (2 samples from 0 - 30 cm + 2 samples from 30 - 60 cm) X 6 blocks = 24 soil samples in total. Each sample was a combination of 3 subsamples.

The soil samples were analysed for particle size distribution, total nitrogen, total phosphorus, total potassium and organic matter. The soil analysis was done at NRM Laboratories, Berkshire using standard methods.

- ***Lettuce Transplants***

Iceberg lettuce (*Lactuca sativa* cv. *Soleison cru*) transplants were seeded on 21/07/2016 and propagated under controlled commercial conditions at G’s Second Willow Nursery (for further information about propagation conditions please see Section 4.1.1.1. The planting crew was followed so that all the transplants were checked for visual irregularities to be re-placed and repositioned according to each treatment. All the plants within the five treatments of the trial were repositioned manually, including the “normal treatment” (Figure 4.12 - (1). Each treatment had 10 replicates.

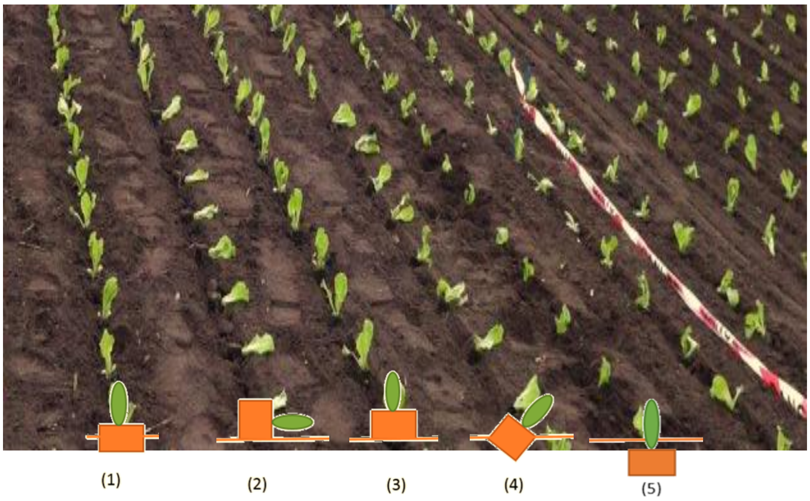


Figure 4.12. Transplants field placement treatments, from left to right; 1) normal, 2) on the side, 3) above soil surface, 4) tilted and 5) Under.

- ***Harvest and assessments***

All lettuce heads from the experimental plots were harvested at maturity, one day after commercial harvest, by cutting the heads using a sharp knife at soil surface. The whole heads were packed in labelled and sealable plastic bags and transported to Harper Adams University, Shropshire. The heads were stored at 4 °C until the next morning and all the assessments were done on Day 1 after harvest. The external leaves of the heads were trimmed along with the unwanted stem in the laboratory, and the enclosed (marketable) heads were weighed using a digital balance (KERN FKB 16K0.1, KERN and Sohn, GmbH, Balingen, Germany). The head circumference was measured using a measuring tape around an equatorial horizontal level parallel to the base (the stem cut) and about 4 - 5 cm above the cut surface. A visual market specification guide (G’s - Tesco market specifications) was used to score the density of trimmed heads on a scale from 1 to 8 using (Figure 4.13). Heads were labelled as ‘misshapen’ if the distribution of internal leaves around the central stem followed the market specifications guide, 0 = acceptable, 1 = unacceptable. The same guide was also used for scoring for the presence/absence of external damage or breakdown (Figure 4.14) and pest damage (Figure 4.15).

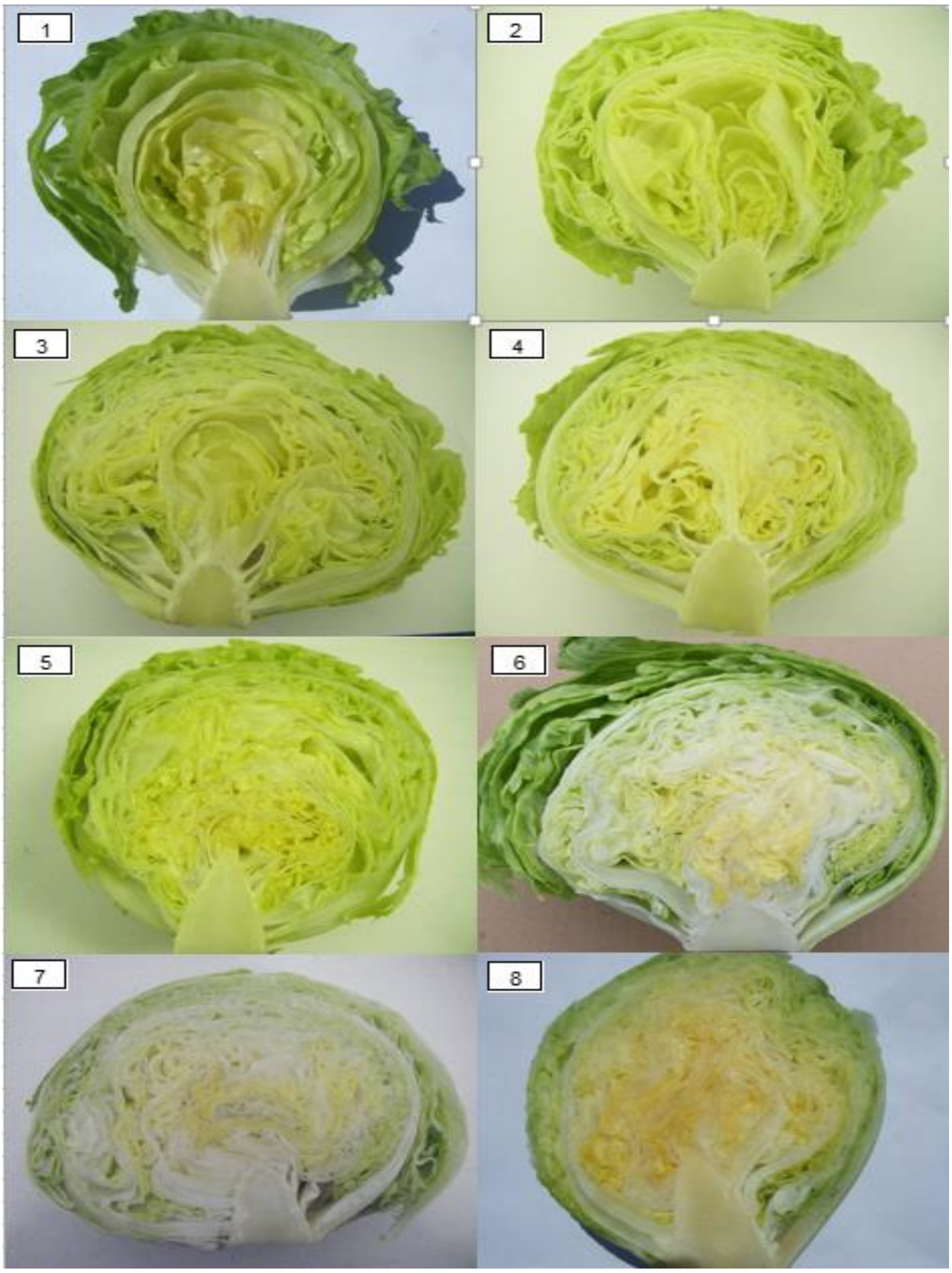


Figure 4.13. G's head density scoring guide showing a scale from 1-8. Source: G’s – Tesco market specification guide.

Figure 4.14. External breakdown in Iceberg lettuce head. Source: G's –Tesco market specification guide.

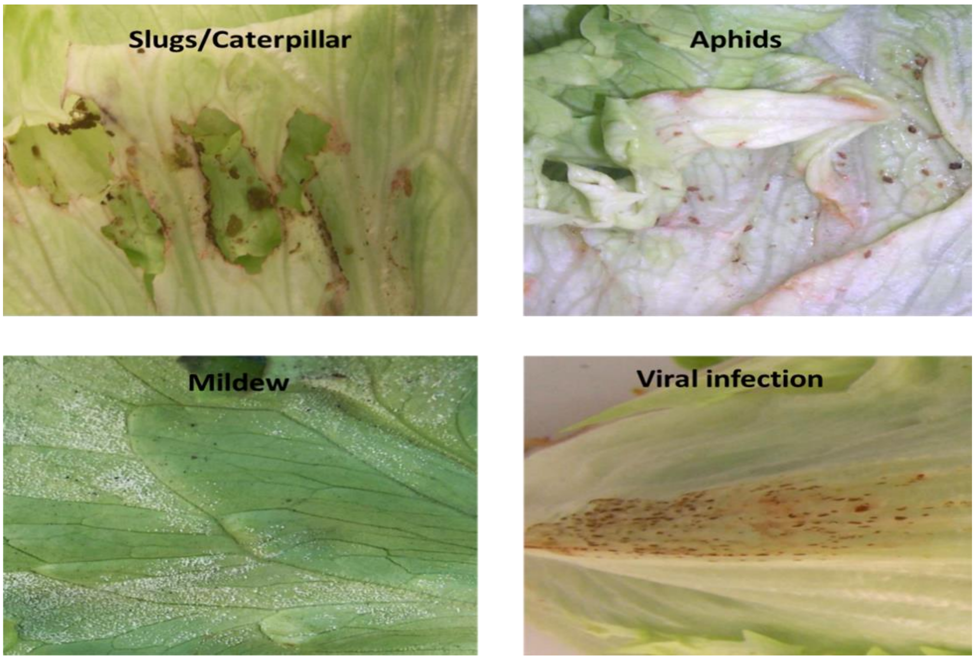


Figure 4.15. Pests / pathogens damage in Iceberg lettuce head. Source: G's –Tesco market specification guide.

4.1.3.2.4 Data Analysis

Marketable head fresh weights, head density and head circumference data, as well as soil properties, were analysed (compared) using ANOVA in GenStat (16th edition, VSN

International, Hemel Hempstead, UK). The proportion of heads with external breakdown damage or pest damage were presented as the sum of scores per treatment.

4.1.3.2.5 Results

a) Soil texture and nutrients

There was no significant block effect on the measured soil properties (silt%, sand%, Clay%, total N, total P, total K, and OM%). Organic matter content was 17.3 % for the top soil (0-30 cm) and 11.2 % for the subsoil (30 - 60 cm) as averaged over 12 samples for each depth (Table 4.7). Soil texture analysis showed that the top soil at 0 - 30 cm classified as Sandy Loam, whereas, the subsoil at 30 - 60 cm was classified as Sandy Clay Loam.

Table 4.7. Soil analysis results for the top soil (0 - 30 cm) of the six experimental plots area for n =12 (each mean is an average of 2 samples per on plot).

Parameter	Minimum	Mean	Maximum	F Probability	SE
OM %	16.2	17.3	18.3	0.9	0.2
Total N % W/ W	0.3	0.6725	0.81	0.3	0.03
Total P mg / kg	513	916.6	1048	0.5	41
Total K mg / Kg	316	433.3	905	0.4	44
Sand %	60	63.75	78	0.5	1.4
Silt %	8	15.83	22	0.7	1.05
Clay %	14	20.42	24	0.4	0.9

b) The trimmed heads

There were no significant block effects on trimmed head weights or quality specifications. There were significant treatment differences in the trimmed head weights, head densities and head circumferences. The Normal and tilted treatments had the highest mean trimmed head weights (576 and 519 g FW / head respectively) whereas the under treatment had the lowest trimmed head weight(309 g FW / head) (Figure 4.16).

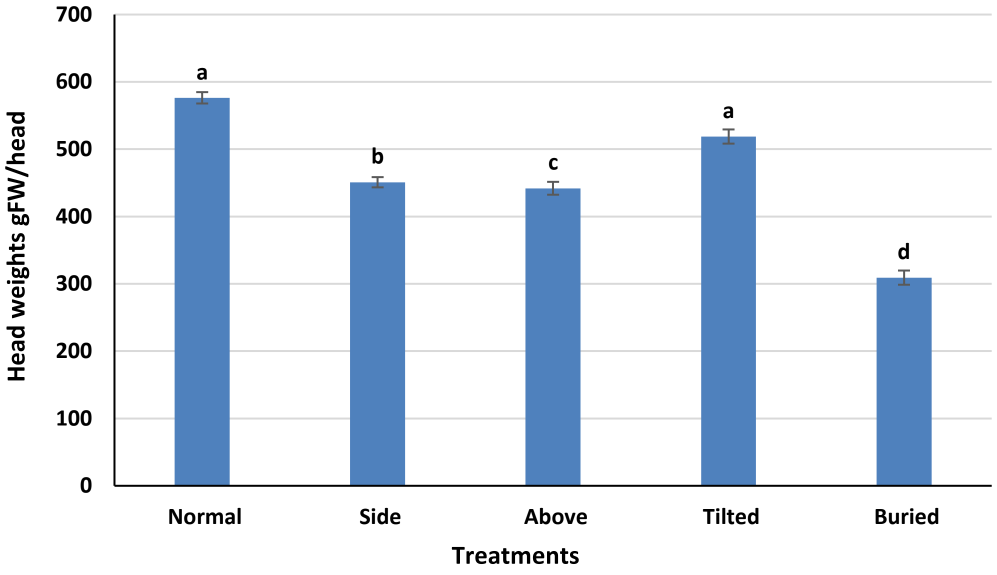


Figure 4.16. Means of trimmed head weights for five different planting positions (P<.001) (n=60). Error bars show the standard error of the samples for n=60.

The circumference followed a similar pattern to head weights. The Standard, Above and Tilted treatments did not differ significantly between each other with mean circumferences 46, 45 and 45 cm respectively. The Under treatment however, had the smallest circumference being an average of 32 cm, significantly smaller than all other treatments (Figure 4.17). It was notable that all these heads were notably oval-shaped (Figure 4.22-d).

Head density showed a different pattern to head weight and circumference. The densest heads were observed with the Under treatment, being significantly denser than all other treatments with a score of 3.9 (Figure 4.18). The Above and Side treatments had similar head density scores of 2.35 and 2.26, respectively and they both had least dense heads. The Standard treatment had a score of 3.27 followed closely by the tilted treatment with a score of 2.9 (Figure 4.18).

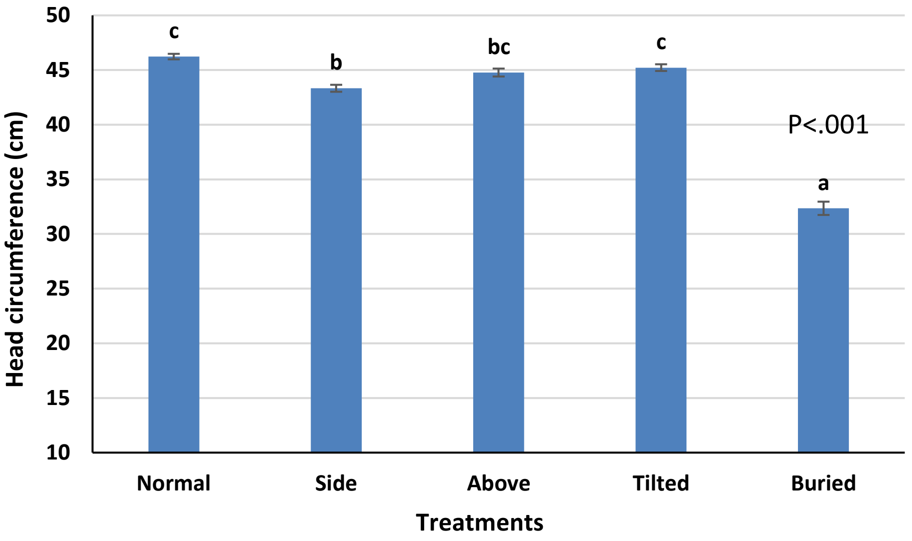


Figure 4.17. Mean trimmed head circumferences for five different planting positions (P<.001) (n=60). Error bars show the standard error of the samples for n=60.

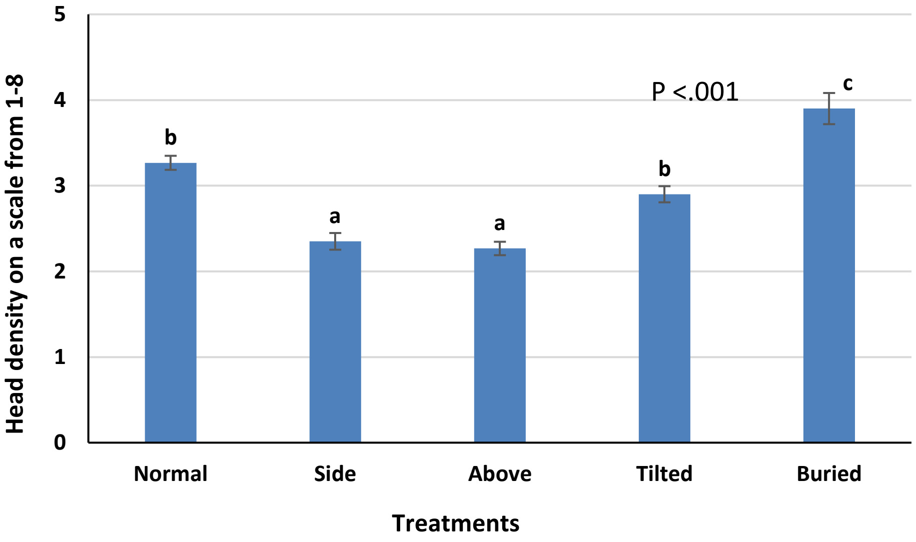


Figure 4.18. Mean density scores for mature trimmed heads for five different planting positions (P<.001) (n=60). Error bars show the standard error of the samples for n=60.

The proportion of misshapen heads showed a clear response. The blocks that were upright (i.e. Standard, Above and Under treatments) had between 28 - 37% misshapen heads. This increased markedly in the treatments where the block was either tilted or laid on the side with all the plants from the Side treatment and 92% of the plants from the Tilted treatment being misshapen (Figure 4.19).

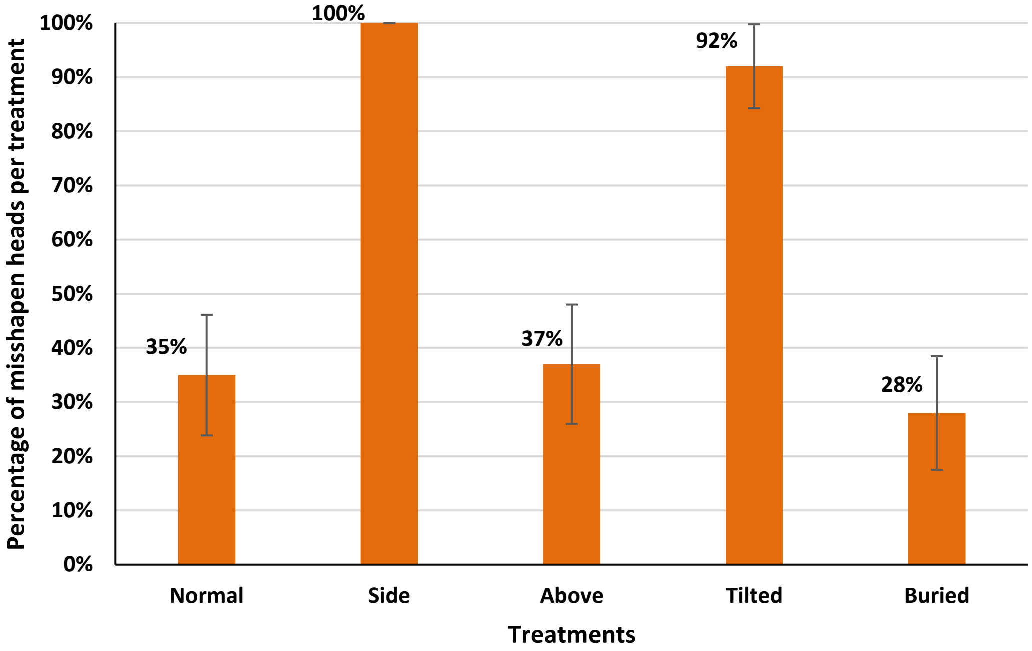


Figure 4.19. The percentage of misshapen heads for each of five planting positions. Presented using the sum of 60 head scores per treatment (n=60). Score: 0 = head shape does not affect marketability, 1 = too misshapen to market. Error bars show the standard error of the samples for (n=60).

The proportion of heads per treatment with external breakdown damage from both moisture and pests was at its highest in the side treatment (9 heads out of 60 for breakdown damage and 31 heads out of 60 with pest damage). The Above treatment had 0 breakdown damage and the Normal treatment had 3 out of 60. Pest damage was at its lowest in the normal and the tilted treatment Figure 4.20 and Figure 4.21.

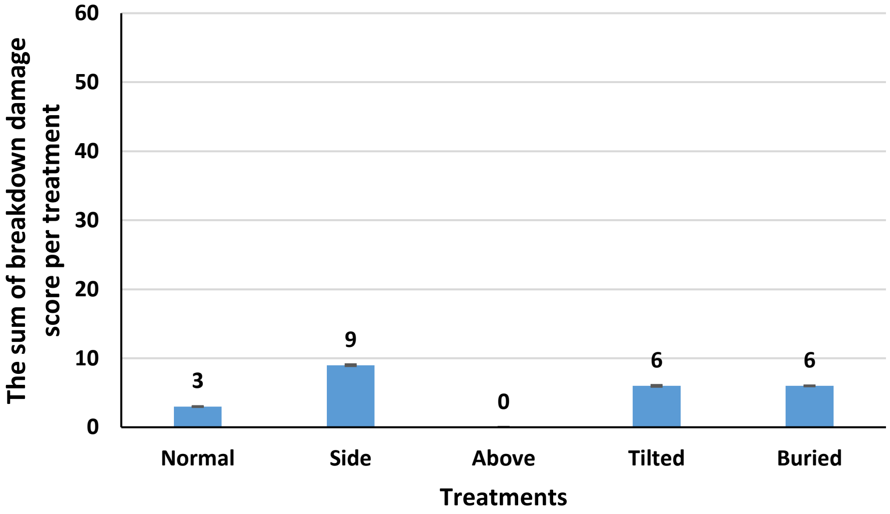


Figure 4.20. The proportion of heads with external breakdown damage per each treatment (n=60). Axis bounds extend between 0 to 60. Score: 0 = breakdown absent, 1 = present. Error bars show standard error for the samples.

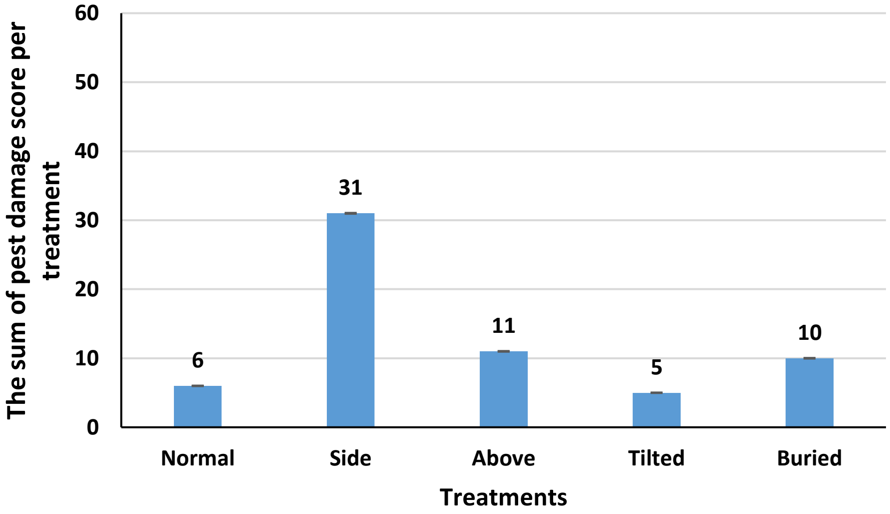


Figure 4.21. The proportion of heads with external pest damage per each treatment (n=60). Axis bounds extend between 0 to 60. Score: 0 = breakdown absent, 1 = present. Error bars show standard error for the samples.

Figure 4.22 shows examples of a frequently encountered head from each treatment with different appearances in lettuce heads that are considered unmarketable. Image (a) shows a markedly misshapen head from the Tilted treatment, where all the head leaves were formed to one side of the central line (the stem). Image B shows the symptoms of ribbiness from the Above treatment. Image C Shows a failure head from the Side treatment. Image D shows a small, dense elongated head from the Under treatment.

Figure 4.22. Pictures showing variability in the marketable quality for positioning treatments.

4.1.3.2.6 Experiment T3 Discussion

In the preliminary study (T3a) there was no significant difference in fresh weight between the treatments despite variable fresh weight means where the tilted treatment had the highest fresh weight, this could be due to more replicates being needed, therefore, more replicates were added in the field experiment T3.

In experiment T3, soil analysis showed no significant difference in the measured parameters between the six experimental plots which suggests that the soil of the experiment area can be considered homogenous, and the absence of difference in the measured crop parameters between the plots supported this suggestion.

The treatments affected the trimmed head weights, head densities and head circumferences significantly at final harvest. Both the normal and the tilted treatments had significantly greater trimmed head fresh weight in comparison with other treatments. The tilted treatment also achieved similar head circumference and head density to the normal treatment. This could possibly mean that the transplants were able to adjust this small tilt (planting fault of up to 45 °) from the upright position, by rotating towards the light and away from gravity under the effect of phototropism and gravitropism where plants tend to orient their above ground shoots towards the radiation and away from gravity (Molass and Kiss, 2009) and therefore, the plants were able to produce as much biomass as the normal treatment. However, the quality of this biomass was different, as not all of the trimmed heads in the tilted treatments were of the required marketability standards, as the tilted treatment had significantly high percentage of misshaping heads (92 %) which could be explained by a disturbance in the morphological process that leads to a successful heart forming and the sequence of changes where the leaves are supposed to become more erect and curved (Wurr *et al*., 1987) instead the leaves were rotating towards the illumination and away from gravity to correct the fault in the planting position. The appearance in terms of pest damage and deterioration) was also compromised in the tilted treatment in comparison to the normal treatment and that is likely to be due to the proximity of the leaves to the soil surface and being exposed to free moisture, soiling and possibly insects.

The transplants that were planted the deepest in the Under treatment (with 1 cm of the green shoot under soil) had the smallest and lightest heads of all the treatments, but the heads achieved the greatest density of all treatments and had the least pest and external damage occurrence of all the treatments. And that is probably due to the small formed head being protected inside several layers of external loose leaves. Meanwhile the density and the oval shape of these heads is very likely to be also caused by most of the leaves growing from the apex under the soil towards the light at early stages of growth which requires further investigation.

In this experiment all the heads were harvested without exceptions. Some of the harvested heads would not be harvested in commercial harvest situations. This was particularly important to take into consideration when comparing the head circumference data and the data of heads harvested from the tilted treatment as these heads show the greatest fresh weight and head circumference values (indicating large heads), as well as similar density to the heads harvested from the normal treatment. However, most of these heads are considered non-marketable due to faults such as misshaping, external damage or hearting failure.

Between 92% and 100% of the trimmed heads of the tilted and the side treatments were misshapen compared with 35% in the normal treatment. However, complete head failure (or heart failure) was most commonly observed in the side treatment which could be explained by the disturbance of the requirements for ideal heart forming of light, radiation which was be more extreme than the tilted treatment due to bigger fault angle from the upright (normal) treatment position (90° angle). This suggestion is supported by (Wurr *et al*., 1987) who reported the hearting stage to be the main stage during which lettuce crop is particularly sensitive to solar radiation and adequate photosynthesis is required to achieve an enough rapid development of the leaves. This would be disrupted by the plants being placed horizontally, the equivalent of falling on the side during planting. This in turn disrupted the speed of leaf arrangement around the stem and the required change of leaf width to length ratio (Wein, 1997 and Ryder, 1999).

The highest trimmed head weight was achieved in the normal and the tilted treatment can possibly suggest that the proportion of the peat block covered by soil in the normal treatment was more adequate to cover the rooting system and give the small plants the most appropriate access to soil nutrients and moisture, in comparison with the side and the above treatments, similarly to a transplant with deeper root system accessing deeper layer of the soil (Johnson *et al*., 2000)

In each of the side and above treatments the peat block was in contact with the soil from one side only, which means the root on the remaining 4 sides had no access to the soil. The peat-block in the tilted treatment was in contact with soil with a larger surface area (a total of three sides) which could partially explain which the tilted treatment had better growth and did not differ significantly from the normal treatment.

4.1.3.2.7 Limitations of this experiment:

An additional collective score should have been collected such as marketable / non-marketable scoring system to clarify where the yield loss would most likely come from. And although density could have been scored as the number of leaf layers divided by the diameter, but then again, the diameter will differ according to the degree of the misshaping.

4.2 Chapter 4 conclusions:

- There is a considerable amount of variation amongst transplants grown from uniform seeds under uniform conditions.
- Transplants that vary in size (length) within the same tray vary in fresh weight. This variability amplifies after transplanting.
- Planting position (in terms of orientation and the depth or the proportion of peat block covered or in contact with soil) affects the marketable yield; relatively uniform transplants develop into variable mature heads in terms of head size, fresh weight and marketable quality and particularly appearance when placed differently at planting.
- The most favourable planting position in terms of the resulting marketable quality was the normal position.

5 Chapter 5. General Discussion, overall conclusions and future work

5.1 General discussion

The aim of conducting this research was to identify the overall causes of in-field variation in lettuce crop, due to the effect of this variability on the harvest efficiency and improve the ability to harvest heads of a uniform size and weight in a single pass. This was also done to examine the type of variability in this crop (temporal vs spatial) and how precision farming could be applied to a short season manually harvested leafy crop such as lettuce. Chapter 1 reviewed the influence of soil properties, climatic conditions, agricultural practices, transplant ages and sizes as well as the interactions amongst these three factors on lettuce crop. The literature review also examined the current knowledge on the use of geographical information and spatial data collection systems, including computerised geographical information systems (GIS) and detailed field mapping with electrical conductivity (ECa) which represented promising and cost-effective tools for putting precision farming into practice.

Four field experiments were conducted to examine the variability pattern in lettuce. Two of these studies were guided by ECa scans and the other two relied on a systematic collection of yield and soil properties especially considering the complex and inconsistent relationship between ECa, soil properties and yield (Corwin *et al.*, 2003; Corwin and Lesch, 2003), and, as well as the complexity that governs interpreting their maps. Two glasshouse experiments were carried out and examined further two of the identified soil properties that affected the yield. Three glasshouse studies were carried out to examine the variability of transplants at propagation and transplanting stage.

In this chapter, a summary of the experiments and a comparison to related literature will be presented. Overall conclusions and limitations of the study will be addressed and further research questions for future work will be recommended.

5.1.1 Identifying variability in soil and lettuce yield on a field scale guided by ECa scans

The aims of chapter 2 and the first two field experiments (FT1 and FT2) were to identify variable management zones using ECa scans and examine the variability in soil properties and crop growth between zones that vary in ECa ranges. And then examine the scale of the variability of ECa zones that could be useful for informing precise management decisions.

Several earlier studies used ECa scans for targeted sampling in the field as these scans coincide normally with soil variation (Doolittle and Brevik, 2014; Grisso *et al*., 2009; James *et al*., 2003; Taylor *et al*., 2003; Earl *et al*., 2003). Soil properties in the studied field varied significantly between the field zones that varied in ECa ranges and that were identified using soil ECa agreeing with these studies. The two experiments used a higher density of soil samples than the density adopted and recommended by James *et al*. (2003) study which reported a strong correlation between ECa variability and soil variability at a higher sampling density (4 - 8 samples per hectare). The difference between the zones from the lowest to the highest ECa values was always significant but it was not always significant between the zone in the middle range (medium ECa) and the other two treatments. Therefore, the critical ranges of ECa variation required further investigation, and a systematic collection of the data was done in FT3 and FT4.

Part of the difference in the growth of young plants that was measured around 35 days after transplanting between these low ECa and the high ECa zones continued to harvest, although decreased and could possibly be due to more overdeveloped rather than underdeveloped young plants. This suggestion could be supported by Kerbiriou *et al*., (2013b) study which found that the variability in size between young plants declines in time particularly for the overdeveloped plants in comparison to normal plants and that overdeveloped transplants do not affect the final yield (Kerbiriou *et al*., 2013b). Meanwhile, the proportion of variation that was recorded at the mid-growth stage and continued to harvest could be due to the proportion of the underdeveloped transplants which could also be supported by Kerbiriou *et al*. (2013b) study findings; that transplants of smaller size affected growth and development continuously as well as the final yield. Therefore, this study suggested that a variation in growth and development that can be recorded at early stages of growth may indicate a variability in the biomass acquired by harvest.

The lack of difference in head density and fresh weight between the medium ECa zone and the high and the low ECa zones could mean that soil factors that change between these zones and resulted in a change in ECa readings had no effect on head density or were not large enough to cause yield variation. Furthermore, head density in lettuce is largely attributed to weather conditions (Wein, 1997 and Ryder, 1999). A greater number of samples could have possibly confirmed whether there was a difference in this parameter that was caused by difference in soil properties.

The most significant observation on the measured soil properties and yield was the similar trend between soil organic matter, clay content and the yield from the lowest to the highest. Where the zone that had the lowest percentage of organic matter and the highest percentage of sand had the lowest yield meanwhile the zone that had the highest yield had the highest organic matter and clay content.

Determining the soil texture class for the mineral fraction of the soil using the particle size distribution test (Natural England, 2008) did not show substantial differences in soil type, the same type of soil existed in three zones across the three examined depths, except for minor differences for Zone C where it was silty clay at 0 – 30 cm depth, instead of silty clay loam as in the rest of the zones and depths.

This difference in clay content can potentially explain both differences in the ECa range and the lettuce fresh weights. De Benedetto *et al*., (2010) found strong correlation between clay content and soil ECa under uniform soil water conditions, meanwhile, Stadler *et al*. (2015) found a strong correlation between ECa and soil texture and moisture. The difference in yield between Zone A (low ECa) and the other two zones (medium and high ECa) therefore, is suggested to be a result of the difference in texture and soil moisture properties, especially since Zone A did not display a lack of the measured nutrients (Mg, K or P) in comparison with Zones B and C. This contradicted the findings of Costigan and McBurney (1983), who associated the difference in lettuce growth on two similar sandy loam soils with reduced levels of potassium and phosphorus. Indeed, Zone C, which had the highest fresh weight was the lowest in phosphorus and potassium. Which draws the attention back to the role of organic matter despite a correlation between the fresh weight and organic matter, magnesium and potassium. But again, both magnesium and potassium were significantly correlated with organic matter. This was also supported by the similarity in the trend between the whole head fresh weight, trimmed head fresh weight and organic matter

The Costigan (1983a) study found that a difference in dry matter was established at early stages of the transplants' life between a natively poor and a fertile site, and that fertilizer application was not sufficient to improve the soil ability to supply phosphorus and potassium to the plants in the poor site to increase the yield. Costigan did not define the difference between the two sites and the term “poor” and “fertile”, however, it is likely to be linked to the level of organic matter or clay content in the studied soils. This is mostly clarified in Dexter (2004a) and Loveland and Webb, (2003) studies. As well as De Benedetto *et al*. (2010) study which found that that clay content is a more reliable measurement for soil in-field variability than bulk density.

The trimmed head fresh weight (TFW) significantly correlated with the total head fresh weight (FW) and soil magnesium content. Meanwhile, FW was correlated with organic matter, magnesium and potassium content. This suggests that soil magnesium has an effect on the production of the lettuce heart, meanwhile the enhanced growth and leaf production in Zones B and C could be associated with better soil organic matter in these zones and could be attributed to a number of reasons from improving the physical quality of the soil (Dexter 2004a) to enhanced rooting intensity and reduced compressibility and machinery damage (Loveland and Webb, 2003). Also, Arvidsson (1998) found that organic matter had more effect on the yield and the physical quality of the soil than soil particle size distribution. Moreover, the correlation between the whole-head fresh weight with Mg and K could partially be a result of or a reason for the correlation with OM and clay %, as these nutrients are known to be strongly interactive with clay minerals and organic matter, which in turn determine their availability for the plants (Brady and Weil, 2006; Marschner, 2012).

There was no correlation between soil pH values and plant growth or yield, which conformed with the findings of Costigan, (1986) where no effect of soil pH on lettuce growth rates was found.

In small scale zones, the difference in soil type between the three ranges of ECa were not substantial. Similarly, the difference between each particle size component was not significant. There was a significant difference in fresh weight and dry weight at mid growth however this difference disappeared at harvest which is suggested to be due to by the growth of the plants where the roots grew outside the small ECa pockets or variable soil properties and accessed the resources in the surrounding areas of the soil which mitigated the variability in the soil conditions. In this scale of soil variation, the roots have a smaller space of supposedly poor soil conditions to overcome. This suggestion is also supported by the findings of Zink and Yamaguchi (1962) findings that lettuce has a relatively higher growth rate during the last 21 days before harvest where 70 % of nutrient uptake occurs in comparison with earlier stages of growth.

It was concluded from these two experiments that field zones that are identified using ECa maps in yield and soil properties. However, if small scale zones with variable ECa values does not reflect important differences in yield or soil properties and therefore are not very useful in supporting variable crop management decisions.

The research questions in this part of the work were;

1) Can we identify variable management zones using ECa scans?
2) Is there variability in soil properties between zones of different ECa ranges?
3) Is there variability in plant growth and development between zones of different ECa ranges?
4) What scale of ECa variability variable management zones / decisions could be identified?

5.1.2 Lettuce variability patterns

There was no significant difference in the marketable yield between the two harvests, and both maps showed consistent spatial patterns, where high yielding areas and low yielding areas remained the same. This suggested that there are underlying soil properties influencing yield distribution regardless of seasonal factors such as soil type. This was particularly evident from north to south and from east to west in both maps.

The variability between individual heads of the same location (plant to plant variation) was eliminated as a source of across field variation at this stage due to small CV values for these data in comparison with the overall spatial yield variability across the field and the difference between the high yield bands and the low yield bands. Which opposed to what was reported by Harwood *et al*., (2010), where the main focus was comparing difference in the CV at early stages of variation to the CV at harvest over the whole field, regardless of the locations and the conditions of the transplants.

There was no statistical correlation between the lettuce yield and the historical wheat yield of the same field, and there was no resemblance between the two yield maps. This was not surprising due to the difference in rooting depths, development stages and crop duration between these two crops; wheat is a long season, non-irrigated crop and lettuce is a short season, irrigated crop with intensive inputs. The relatively short crop duration for lettuce of 5-8 weeks from transplanting to maturity contrasts with that of wheat i.e. 7-11 months. As a consequence of the longer growing period, long season crops such as cereals access a greater depth of soil and the yield is more dependent on the sufficient extraction of subsoil water, whereas mature lettuce stands in the field for a very short term and the final yield is less dependent on the subsoil water and more sensitive to external factors during early stages (Costigan and McBurney., 1983). This could also explain the difference in the degree of success for using ECa scan in yield prediction for long season crops and not for lettuce as was found in FT1 and FT3.

5.1.3 Soil and yield data collection methodology and the use of soil ECa scans

In experiments FT3 and FT4, some of the soil physicochemical properties that can affect lettuce growth and yield were examined and mapped along with the yield of two successive crops in the same field. The purpose of the maps was to predict lettuce yield variability patterns in order to provide information for targeted solutions in spatial and temporal aspects. The purpose of statistical analysis applied was to identify a limited number of soil properties that had the key influence on the yield.

The experiments FT3 and FT4 used a regular grid sampling (20 m X 24 m) that was more intensive than the grids that are commonly used in commercial settings e.g. 100 m X 100 m grids (Earl *et al*., 2003) or an irregular grid spaced at densities from 1 to 8 samples per hectare James *et al*., (2003).

Unlike cereals and long season crops, where yield maps appeared to be available for farmers and were investigated by several studies much earlier (Stafford *et al*., 1996; Taylor *et al*., 2003; Earl *et al*., 2003 and Stadler *et al*., 2015), mapping leafy crops and particularly lettuce has posed a challenge, due to the manual harvesting of this crop and the yield mapping has not been developed sufficiently. Panagopoulos *et al*., (2006) study was able to localize some zonal soil problems (mostly moisture related) in a salinized lettuce field and recommended variable management or amendment decisions to optimise the overall yield across the field.

Shallow and deep ECa values correlated strongly, and both had similar ranges of ECa values and showed similar spatial patterns (maps). However, there was no correlation between ECa at either depth with the yield. Supporting the results of the 2014 experiments (FT1 and FT2), suggesting that ECa scans are not very useful for predicting lettuce yield.

Corwin *et al*., (2003) reported that the correlation of ECa with crop yield is not consistent (it correlates with the yield of some crops and not others, or it might correlate with the yield in a certain field and not another), as ECa might be affected by soil properties that may not affect the yield in a certain field or in certain zones of a field. For example, in this field Redmere P57, ECa could be a result of soil properties that have not been measured or do not correlate with lettuce yield such as the depth of top soil or the depth of a water table (Corwin and Lesch, 2005).

Despite the similarity between the two ECa scans (depths), shallow EC did not correlate with any other soil properties. Meanwhile, deep EC correlated with soil moisture and clay content. This conformed to some of research findings where ECa was suggested to be mainly a function for clay and moisture contents of the soil (De Benedetto *et al.,* 2000; Godwin and Miller, 2003; Brevick *et al*., 2006). Indeed, the soil profile pits showed the difference between these two layers.

5.1.3.1 Bulk density

Bulk density values over the whole field ranged between 0.1 to 0.3 g / cm^3 with a mean value of 0.2 g / cm^3, which is considered normal for organic soils due to the markedly light weight of organic matter when dry (Brady *et al*., 2006). In this study, bulk density correlated negatively and significantly with clay content which conforms to a previous study (Ruehlmann and Korschens, 2009) that reported a significant negative relationship between soil bulk density and clay content.

In field conditions in FT3 and FT4, bulk density correlated negatively with lettuce yield, despite the normal levels of bulk densities found in the studied field. This suggested a compaction effect; loss of large pores, water retention capacity of the soil (Dexter, 2004a) or hindering of root elongation within the soil (Marschner, 1995). However, for a relatively loose soil with high levels of organic matter, this contradicts the findings of (Arvidsson, 1998) who reported an increase in barley yields in traffic compacted soils with higher organic matter, suggesting that the organic matter reduced soil compaction and improved the yield. In FT3 and GH1 bulk density correlated negatively with organic matter which confirms the findings of Arvidsson (1998) and Walter *et al*., (2015). Therefore, the negative correlation between the yield and the bulk density in this field which does not show compaction results could also be linked to soil water infiltration and drainage rates which relates back to the loss of large pores. Furthermore, there are substantial differences between barley and lettuce crop characterised by root depth and the duration of standing in the field.

Identifying the critical ranges of bulk density that affects lettuce yield within the narrow range of results (0.1 to 0.3 g / cm^3 and the value of 0.2 g / cm^3 as an average) found in Redmere P57 posed a challenge. Measuring bulk density alone can be very difficult as highlighted by Lark *et al*. (2014) due to the level of precision needed during the extracting and handling of the soil cores, and also due to the unavoidable disturbance that occur to the samples during this process. This makes it very difficult to use conventional bulk density assessments to identify in-field variation in bulk density within such a narrow range of values. And due to variability in organic matter across the field which will affect the measurements as explained by (Dexter, 2004a) in the organic matter section. And this requires further investigation.

5.1.3.2 Organic matter

There was a considerable difference in organic matter between the top and the subsoil and this was also evident when opening the profile pits. However, there was also a strong correlation between the two, with similar spatial distribution

The top 30 cm of the soil had between 21 % and 53 % OM, which is considered as fertile soil (Loveland and Webb,2003) and considered from marginally high to high in organic matter (Thompson, 2007). The following layer of soil (the subsoil) at 30 to 60 cm depth had OM that ranged from 6 % to 38.7 %. And here the difference posed more variation in soil type despite the similar range of difference (about 32 % between the lowest and the highest measured OM %) as a soil with 6 % organic matter is classified to be on the border between mineral and organic mineral soil meanwhile the soil with 38.7 % is classified as sandy peat or loamy peat (Natural England, 2008). This difference however, even in the top layer, might result in effects on growth conditions such as nutrient and water holding capacity, rootability, and drainage, etc.

The difference in the organic matter concentrations between the two soil depths may predominantly arise from greater breakdown and decomposition activity due to better aeration in the topsoil in comparison to the subsoil (Davies *et al*., 1993).

The similarity in OM spatial pattern could indicate some further spatial variation in soil texture. A correlation between the spatial variability in organic matter and the variability in soil texture was reported by Qiu *et al*, (2016) who also concluded that the variability in soil texture is a key factor influencing the in-field variability in organic matter. However, the difference in the ranges of organic matter between the two depths in this study makes the comparison between the two maps of limited benefit.

Both soil EC and OM values were greater in the southern part which could suggest possible effects for the organic matter content on the ECa readings, through its effect on soil moisture properties which in turn affect the conductivity (Stadler *et al*., 2015).

Dexter (2004a) showed that the effect of organic matter content on soil microstructure differs when clay content differs, and concluded that the effect of organic matter on the soil microstructure was optimal when soil clay content was lowest. The study found that 1.2 % and 4.2 % OM to be the critical levels for soils at which poor physical properties start to occur. Which adds to the complexity of studying other soil properties as was also found by Dexter (2004a) that the variability in organic matter resulted in changes in the densities of soil samples and comparing the physical or mechanical properties of the soil from various locations within the fields problematic, also due to various water contents a s a result various contents of organic matter in the soil samples can result in (Dexter, 2004a).

The results from Experiment GH1 indicated that variability in organic matter content across the field Redmere P57 possibly resulted in variable bulk densities across the field. As a strong negative correlation was found between the OM % and the treatment bulk densities g / cm^3, The R^2 of 0.99 suggests that 99 % of variation in bulk density could be explained by the variation in organic matter content. Increasing organic matter content reduced the bulk density from 1.87 g/cm^3 (the maximum density obtained) in treatment T1 (1% OM) down to 0.32 g / cm^3 (the minimum density obtained) in treatment T10 (91% OM). Which agrees with (Arvidsson, 1998, Dexter, 2003a and Ruehlem and Korschens, 2009) and was also supported by the results from Experiment FT4, where the spatial distribution of bulk density was inversely associated with that of the organic matter; i.e. bulk density was low where organic matter was high.

The values of bulk densities in Redmere P57 and experiment FT3 were difficult to compare to the bulk density results from the experiment GH1, due to most of the field values being below the GH1 values which was explained by the difference between field and pot conditions in Ch2 discussion. However, relatively speaking, the significant difference that was found between each two successive OM treatments under the addition of 10 % OM confirms the reducing effect for OM on bulk density which was reported in earlier studies including Arvidsson (1998) and Loveland and Webb (2003).

5.1.3.3 Nutrients

Three total nutrients were measured in this study, N, P and K. Lettuce yield correlated only with total K and total N in the subsoil at the 30 - 60 cm soil depth.

There was a strong correlation between the topsoil and subsoil total nitrogen, but the level of total N was significantly higher in the top 30 cm. This might be due to naturally higher organic matter content and improved aeration and mineralisation in topsoil (Brady and Weil., 2006), or due to a limited leaching of applied N into the subsoil with drainage water). Total K, however, was significantly higher in the subsoil than in the topsoil with a strong correlation between K values at the two layers. The difference in K between the two depths and the fact that total K was lower in the topsoil could be a result of crop root uptake and farming practices or manipulation to adapt to crop needs such as fertilising the soil or incorporating the previous crop residue during tillage (Brady and Weil., 2006).

The correlation between the yield and K agrees with the study of Costigan and McBurney, (1983) which related improved lettuce growth with native potassium and phosphorus in the soil. However, in this study, the correlation matrix showed no relation between the yield and the total P. This might be due to the P nutrient being more important at early stages of growth and the establishment of the transplants in comparison with subsequent growth, development just before harvest, where Nitrogen is the most influential nutrient (Ryder, 1999). The correlation with total N is expected due to the importance of this nutrient in the growth and development of plants in general and leafy crops in particular such as Lettuce (Marschner, 1995 and Ryder, 1999) where the harvested part is the photosynthetic organs. Furthermore, this correlation with total K and total N could also be linked to the correlation with OM

However, without data about the availability and mobility of these nutrients it would be challenging to interpret these results further. Instead, a comparison study is needed where the effect of total, available nutrients as well as their mobility could be investigated while taking into consideration soil variability or different soil types.

5.1.3.4 The multilinear regression analysis with features selection (MRAFS)

Bulk density was the strongest predictor of trimmed head fresh weights for both yields (FT3 and FT4), followed by silt concentration of the mineral fraction of the soil, then the interaction of the total nitrogen with the total phosphorus at the top soil for FT3, and total nitrogen then silt at the subsoil for FT4. These were followed by the interaction between organic matter at both soil depths with nutrients and the interaction of N with P and K on the yield.

The results after excluding bulk density showed that the topsoil total phosphorus (P1) was the strongest predictor of the yield for both FT3 and FT4, which agrees with Costigan and McBurney (1983).

The FT3 model was stronger than the FT4 due to its higher R^2 values and lower RMSD values, moreover, the yield in FT3 was collected instantaneously with soil data.

The finest clay particles from (0.5-0.6 μm) had the strongest effect on FT3 yield. Whereas, the finest silt particles (2.01 to 2.6 μm) had the strongest effect on FT4 yield. The fine silt particles of the size 2.5219 μm of the subsoil were again the strongest predictors of trimmed fresh weight for both FT3 and FT4

The effect of the finer particles in the soil on the yield is likely due to the larger surface area where the fine clay particle sizes have more ability to adsorb more nutrient, gases and moisture with their specific surface phenomena (Brady et al., 2006) - their ability to hold cations is a key part of soil fertility. Clay was much lower in the subsoil than in the topsoil, which probably explains why the strongest predictor of the yield from the subsoil particles was the fine silt.

Replacing the sand, silt and clay contents in the analysis with the actual particle sizes continued to show topsoil phosphorus (P1) as the strongest predictor of the FT4 and the topsoil OM the strongest predictor for FT3. However, it also resulted in reduction of the model accuracy by reducing R^2 and increasing the RMSD values. This could also be due to separating the organic matter from the texture effect which is an important component of the texture factor.

Considering that nutrients are the most practically modifiable inputs of the studied properties, a model was fitted to the nutrient data to test which nutrient predictor variables provided the highest (predicted) yield when it was increased while keeping the rest of the variables constant. This allowed examination of the influence and the scale of the response. The results showed that the highest yield response can be achieved when the subsoil nitrogen (N2) was increased by 0.5, 1, 1.5 and 2 mg kg^{-1} respectively, and while keeping the other variables constant. The model was used to predict yield by using 20 % increase of the topsoil nitrogen. Considering that topsoil nitrogen is an easily achievable increase in the field and due to the highly predicted yield response to nitrogen at both depth generally. The predicted yield increased with the increase of total nitrogen in certain locations within the field whilst it decreased in others. The decrease in the yield is very likely to be due to nitrogen toxicity (Hoque *et al.*, 2008 and Marschner, 1995).

Calculating the values using one of the low yield sampling locations (location number 3) as a reference point was done in ArcGIS by increasing the levels for individual variables, by 5 %, 10 % and 20 % each time for the model that included bulk density and for the strongest predictor variables in this model, there has been a yield decrease with the increase of bulk density and silt content. Whereas, Nitrogen increase, however, had no effect on yield response. The model that excluded bulk density showed a modest yield increase, most notably when increasing P1, K2 and Sand1, whereas increasing OM for the topsoil had negative effect and increasing it in the subsoil had negligible or no effect which conforms to Costigan (1986) study that found a negative effect to soil organic matter on the relative growth rate of lettuce, and the percentages he reported were 28.5 % and 45.7 % of organic matter. However, Costigan’s study only comparing lettuce growth rate on a variety of soil types including two organic soils and there weren’t enough organic matter data to support these findings. Costigan study did not explain why these levels of organic matter were associated with poor crop performance however, it suggested that an increase in cation exchange capacity of the soil that had possibly reduced the availability of some micronutrient cations to the plants or some unfavourable increase in microbial activity or higher soil temperatures due to darker colour of the soil.

The sand proportion of the mineral fraction of the soil appeared to have positive impact on the yield according to the model calculation in FT3. The maps also showed correspondence between high sand content and high yield in the north part of the field on the west to east orientation. However, both in the first field FT1 experiment in Redmere P36 and in the glasshouse experiment GH2 sand showed negative effect for the sand on the yield. In FT1 the zone that had the highest yield had the lowest sand percentage, and in GH2 there was a strong negative correlation between the attained fresh weight (g / plant) 14 days after transplanting and the added sand rate (R = 0.7) where 84 % of the variance was accounted for by the sand treatments (R^2 = 0.84).

Sand treatments affected the water holding capacity at pot capacity, where the treatments with the greatest sand proportion had the lowest water content. Which supports the suggestion that soil moisture retention is affected by the varying sand percentage in soil across the field. However, since the drained solution was not tested, and no test was done to the nutrient contents in the substrate, it cannot be confirmed whether the reduction in growth is only due to the reduction of the available water or also due to the dilution of the nutrients. The positive effect for the sand in Redmere P57 in FT3 is suggested therefore to be linked to sand benefits in waterlogging conditions or poor drainage.

Irrigation treatment had no effect on plant fresh weight, this confirmed the findings of Gallardo *et al*., (1996), which reported that lettuce was not sensitive to excess irrigation at around 24 days after planting from seeds (which coincided to the first week of the experiment GH2). Meanwhile Gallardo *et al*., (1996) found that the period in which lettuce was particularly sensitive to the irrigation was the last three weeks before harvest which was not covered in this experiment.

5.1.1. Examining variability in lettuce transplants (during propagation and at transplanting) and the effect of this variation on subsequent growth and final yield

The aim of chapter 4 was to examine lettuce variation at early stages of growth. Plant to plant variability was investigated before and at the transplanting stage, as well as the effect of this variability on lettuce growth and development. Furthermore, the effects of variable depths of planting and positioning of the propagated transplants on the field the final yield and the marketable quality of this yield was investigated.

The research questions in this part of the work were;

1) How variable lettuce transplants are in size within the propagated trays?
2) Does this variability follow a certain pattern?
3) Does this variability continue to the field?
4) Does variable planting / placements in the field result in variability in the marketable lettuce heads?

Transplants that were grown within the same tray and from the same seed batch and propagated under the same conditions showed large coefficient of variation (CV) values in Experiments T1a and T1 when the above ground part of the plants was weighed.

The CV values remained relatively high over three days of growth, despite decreasing, while the mean weight of transplants increased. This suggested that the variability declines with age, however, these three days data of this experiment were not enough to predict to what extent this variability will decrease over time or whether it will disappear completely.

The variability in fresh weight amongst transplants conformed to findings of Harwood *et al*., (2010) which suggested that there is natural variation amongst transplants and described this as inherited plant to plant variation and concluded that it accounted for most of the variation in transplants. However, Harwood *et al*., 2010 overlooked the fact that in field situations, the field could be planted by several patches of transplants that might differ in days or had undergone variable conditions during the process as well as not taking into consideration the effect of soil and field variability. Moreover, modern lettuce varieties have been bred for optimum yield under high input systems with small and shallow roots (Johnson *et al*., 2000; Gallardo *et al*., 1996; Kerbiriou *et al*., 2013) which makes lettuce seedlings and transplants highly sensitive to fluctuations in the external conditions such as moisture, nutrients. This emphasise the importance of understanding field heterogeneity.

There was no difference between the transplants grown on the edge and in the centre of trays so the hypothesis that transplants on the tray edge were smaller than the plants in the centre of the tray was not supported. Although the mean values were always smaller on the edge than in the centre, the individual plant values were not always smaller at the edge. However, the large value of the CV necessitates investigating the reasons behind this variability and how could the micro-ambient conditions be used to affect this variation (i.eg. peat block size, tray size, temperature and moisture distribution, shading from tray edges or glasshouse poles, etc.)

Experiment T2 aimed to investigate whether this particular type and value of difference in transplant (from 0.02 to 4.38 g / plant in the experiment T1a and from 0.08 to 1.79 g / plant in the experiment T1) would result in subsequent variation in growth and development after 14 days growth. Targeting the 14 days after planting was done to increase the length of observation in comparison with T1a and T1, and to examine the grower's observations that suggested that the two weeks old plants (in the field) can be distinguished in terms of which plants are not going to mature and develop in size at harvest time when the majority of the heads in the field are ready for harvest (Rob Parker, pers comm).

There was a significant difference in the estimated starting fresh weight between the small and the large group of transplants ($P < 0.001$). This variability could not be simply explained by the reasons suggested by Wurr *et al*., 1987 and Wurr and Fellow 1991, as both studies suggested that transplants age, temperature, solar radiation are the main causes of variation between batches of transplants (Wurr reported that 98 % of the differences the growth of lettuce plants after seed emergence were accounted for by temperature). This was because the transplants in experiment T2 were sourced from the same batch and the same location in the glasshouse where they had undergone (relatively) the same environmental conditions and held for the time of the experiment under relatively uniformly controlled environment in comparison with the differences imposed on the transplants by Wurr *et al*. (1987) and Wurr and Fellow (1991) studies. The difference between the small and the large group of transplants supports more the inherited plant to plant variation explanation that was given by Harwood *et al*. (2010). However, the limited data available about the exact seed emergence date and information about the uniformity of the propagation or field conditions in the study of Harwood *et al.* (2010) suggests that there could be an effect to the precise emergence time of the seeds and the micro climate within the glasshouse or trays. At 14 days after transplanting, there was a significant difference in the fresh weight between the small and the large group of transplants (P < 0.001). The resulting figures suggest that 0.1 g / plant average difference in the starting weight between the small and the large group of transplants multiplied into an average difference 20 g / plant over 14 days of growth. This supports the findings of Costigan and McBurney's, (1983) and Kerbiriou *et al*., (2013) about the importance of initial growth as the established difference in dry matter building and size development has been shown to persist to harvest (Costigan and McBurney's, 1983 and Kerbiriou *et al*., 2013) which contradicts to some extent with both Wurr *et al*., (1987) and Wurr and Fellow (1991) who suggested that variability in the final yield in the field is a mainly combination of both the growth stage of transplants and the ambient conditions.

Experiment T3 was done to examine whether variable placement of transplants in the soil would result in variability in the subsequent growth and development. There was no significant difference in the soil or the crop parameters between the six experimental plots which suggests that the soil of these plots can be considered homogenous. The variable transplant placements and positioning in the field resulted in significant variability in the trimmed head weights, head densities and head circumferences significantly at final harvest. The tilted treatment achieved similar head circumference and head density to the normal treatment. This suggested that the plants were able to adjust this small tilt (planting fault of up to 45 °) from the upright position, by rotating towards the light and away from gravity under the effect of phototropism and gravitropism, where plants tend to orient their above ground shoots towards the radiation and away from gravity (Molass and Kiss, 2009) and therefore, the plants were able to produce as much biomass as the normal treatment.

However, the tilted treatment had significantly high percentage of misshaping heads (92 %) which indicated a disturbance in the morphological process that leads to a successful heart forming and the sequence of changes where the leaves are supposed to become more erect and curved (Wurr *et al*., 1987) instead, the leaves rotated towards the illumination and away from gravity to correct the fault in the planting position. The appearance of the tilted treatment was also compromised in terms of deterioration and pest damage in comparison to the normal treatment and that is likely to be due to the proximity of the leaves to the soil surface and being exposed to free moisture, soiling and possibly ground insects. The fact that all heads were harvested in this experiment should particularly be taken into consideration when comparing the weights and the sizes of heads between the tilted and the normal treatment, as some of the harvested heads of the tilted treatment would not be harvested in commercial situations due to faults in the marketable quality such as substantial misshaping, external damage or hearting failure.

The greatest planting depth in the Under treatment (with 1 cm of the green shoot under soil) gave plants with the smallest (weight and circumference), but the heads had the greatest density and the least pest and external damage occurrence of all the treatments. And that was probably due to the small formed head being protected inside several layers of external loose leaves that failed to heart. Meanwhile the density and the oval shape of these heads is likely to be caused by most of the leaves growing from the apex under the soil towards the light at early stages of growth. Therefore, the planting depth of lettuce transplants and the resulting shapes require further investigation.

Between 92 % and 100 % of the trimmed heads of the tilted and the side treatments were misshapen in comparison with 35 % in the normal treatment. Complete head failure (or heart failure) was most frequently observed in the side treatment which very likely resulted from the more extreme disturbance to the heart forming of process in terms of light-resource capture and gravity effects on the plant due to a bigger fault angle from the upright (normal) treatment position (90 ° angle). This suggestion is supported by (Wurr *et al*., 1987) who reported the hearting stage to be the main stage during which lettuce crop is particularly sensitive to solar radiation and adequate photosynthesis is required to achieve an enough rapid development of the leaves. Which was disrupted by the plants being placed horizontally aka falling on the side during planting. This in turn disrupted the speed of leaf arrangement around the stem and the required change of leaf width to length ratio (Wein, 1997 and Ryder, 1999).

The greatest fresh head weight that was achieved in the normal and the tilted treatment suggest an effect to the proportion of the peat block in contact with in these two treatments as this proportion appeared to be more adequate to cover the rooting system and give the small plants sufficient access to soil resources in comparison with the side and the above treatments (Johnson *et al*., 2000). In the side and the above treatments, the peat block was in contact with the soil from one side only, whilst the remaining 5 sides had no access to the soil. The peat-block in the tilted treatment was in contact with soil with a total of three sides which could also be an additional explanation of why the tilted treatment did not differ significantly from the normal treatment in terms of the fresh weight. The transplants with deeper root system accessed deeper layer of the soil and the peat-block was completely covered with the soil, however, covering 1 cm of the green shoot appeared to have caused a decrease in the size and the weight of the heads below the marketable quality, however the marketability of these heads require further research should the growers or the supermarket consider a differently sizes Iceberg lettuce of regular shape and undamaged appearance.

It is therefore, recommended for growers to check field variation in terms of soil type, levels of organic matter by carrying out targeted sampling and possibly excavating profile pits in areas of variation, in order to decide upon the site-specific amendments needed. Additionally, ensuring transplants uniformity and possibly discarding transplants at

5.2 The Overall Conclusions

- ECa scans helped identifying different soil zones within the studied field and enabled targeted soil sampling which revealed significant variations in soil properties and lettuce yield. However, they were not sufficient to underpin the underlaying causes of these variations, as no direct correlations were found between ECa values and the measured soil factors or yield. This also suggest that ECa in this field is a function of other soil properties that are not determinants of lettuce yield.
- Field areas that varied in EC ranges varied statistically in percentages of clay content and in the Mg, K and P. Plant growth varied between the zones midway through growth (35 days after planting) and at harvest despite the decline in the difference at harvest.
- Demarcating variable soil-EC zones at a smaller scale (smaller than 3 m^2) was inefficient for studying the potential for increasing lettuce crop uniformity through variable management.
- Lettuce yield in this study varied spatially and not temporally. The variability pattern of lettuce yields was consistent over the zones of the two crops, suggesting that yield distribution was mainly driven by underlying variation in the properties of the field soil rather than by seasonal variation in moisture and weather conditions.
- Variable field zones could be identified using soil EC scans, maps of soil properties, as well as the yield maps. However, overlaying the maps of different parameters did not show a satisfactory conformance and did not reveal unified zones of variation in the field suggesting that the yield could be driven by one factor in the field and different factors in others. Therefore, the benefits of relying exclusively on the maps will always be limited without taking into consideration scientific and statistical analysis which would be challenging for the growers mainly when justifying the costs.
- Both shallow and deep ECa maps can be used to identify variable field zones due to strong correlation between the two layers of readings and also due to a considerable correspondence between the two maps.

- Statistically, bulk density was the strongest predictor for both yields of lettuce trimmed head fresh weights, followed by silt concentration and total nitrogen. However, organic matter variation appeared to have played a key role in the overall soil variation in the field through a complex relation with bulk density (the strongest predictor of the yield), texture and water holding properties. This was concluded from maps comparisons, literature review and the rank of organic matter in the multilinear regression model.
- Organic matter suggested role in yield variation was also supported by the results of the glasshouse experiment GH1, where variability in organic matter contents between the treatments resulted in variability in water loss rate via drainage, the amount of water lost, the duration to reach field capacity and the amount of water held at field capacity. As well as, the strong negative correlation (R = 0.999) between organic matter percentage and bulk density g / cm^3, where most of variation in bulk density was accounted for by the variation in organic matter content.
- Variability in soil texture and particularly the mineral fraction of the soil also appeared to have an important influence on yield variation. This was identified by the clear difference in soil types and yield between the zones in 2014 experiments FT1 and FT2, as well as the frequent appearance of silt content, sand and the fine silt particles statistical model. The glasshouse experiment GH2 showed that the transplants fresh weight at 14 days after transplanting correlated strongly and negatively with the added sand rate (R = 0.7) where 84 % of the variance was accounted for by the sand treatments ($R^2 = 0.84$).
- The total phosphorus in the topsoil was the strongest predictor of the yield for both crops after bulk density was excluded from the model.
- There is a proportion of the variation in lettuce yield starting at early stages of growth, before and at the transplanting in the field
    - Transplants grown from uniform seeds under uniform conditions showed considerable variability and high coefficient of variation.
    - Variability of transplants within the same tray in terms of size and fresh weight amplifies after transplanting.
    - Variability in planting position (orientation, depth or the proportion of peat block in contact with soil) results in variability in the marketable yield and the quality of this yield in terms of head size, regularity, density and appearance.
    - The most favourable planting position in terms of the resulting marketable quality was the normal position.

5.3 Overall limitations and prospect for future work:

This research highlighted the complexity of interpreting soil maps in relation to yield maps for a short season crop such as Iceberg lettuce, where the crop stands in the field for a very short period of time and even shorter time at full maturity. Where the short-term effects and temporal interactions of various soil properties can have more influence on the crop than the constant underlaying soil properties that are relatively slower to change through the whole year. Therefore, a replication of this study with more focus on the temporal changes in soil conditions can possible hold more answers. This also highlights the importance taking into consideration the specific conditions of each field when making precision management decisions for such a crop. A superimposed complexity is that mapping technology for Iceberg lettuce has not been fully developed yet and that the harvested part is covered under several layers of loose leaves that need to be manually removed in order to assess the formed Iceberg head.

The thesis discussion also highlighted the need for more information about in-field variability in organic soil and the physicochemical and electrical properties of these organic soils where little work has been done in comparison with mineral soils. Furthermore, repeat of the glasshouse experiment that investigated different levels of organic matter is needed over a longer period of time and that involves plant growth and chemical analysis of the soil to obtain more information about the effects on crop growth. Similarly, for the glasshouse experiment that studied the effect of sand content on moisture holding capacity and lettuce growth, where nutrient analysis for the drained solution would provide information about the nutrients holding capacity for a soil with variable sand contents and provide a ground for understanding where the growth reduction primarily comes from (water holding capacity vs nutrients holding capacity). Similar field work is needed with focus on the availability and mobility of major and minor nutrients across the field. As the nutrients analysed for this study were total nitrogen, potassium and phosphorus primarily for gaining a general understanding of the fertility and the general status of the nutrients in the studied field soil.

The ECa scans that were used for this research were produced by a commercial horticultural consultancy service where the spacing between the readings were relatively wide, and only one scan per field was examined, whereas repeated scans and of greater intensity would potentially carry more information and would also add more accuracy and purity to the maps and the zones boundaries.

Further work also is also proposed with regards to transplants variation at early stages of growth as well as the effect of planting depth on transplants variability and final yield. This research has revealed considerable variability amongst transplants that are known to the grower as uniform as these are grown from the same genetic material under the same controlled conditions before leaving the propagators and showed that this variation in size increases after transplanting. However, the reasons for this this variability were not investigated. Further work is needed to examine the precise conditions of propagating lettuce transplants such as light intensity and distribution within the trays, the effect of variable sizes of peat blocks and the spacing of the seeds and the population per tray.

Lettuce transplanting depth across variable soil types as both shallow and deep transplants produced heads with a considerable regularity with difference in density investigation is needed to identify at which depth (and why) the density variation occurs and how could this depth be benefited from to produce better and more uniform yield in adaptation to variable soil conditions.

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