Optimizing winter oilseed rape nitrogen management in the mild Atlantic climate of Ireland

By

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Declaration of Originality

I hereby declare that this thesis was not previously submitted as an exercise for a degree at South East Technological University or any other University and I further declare that the work embodied herein is based on my own independent effort, except where I have received help as stated in the acknowledgements and text

Shiva

Signature: ____

Date: 26th August 22

List of Abbreviations

95CI	0.95 Confidence Interval
˚Cd	Centigrad days (Degree Days)
AAB	An Alternative for BBCH
AAN	Additional(ly) Available N
ADAS	Agricultural Development and Advisory Service
AHDB	Agriculture and Horticulture Development Board
ANB	Apparent Nitrogen Balance
BBCH	Biologische Bundesanstalt, Bundessortenamt und CHemical Industry
BC	Break crop
BER	Break Even Eatio
BFS	Beam Fraction Sensor
C	Carbon
CAN	Calcium Ammonium Nitrate
CH4	Methane
CM	Canopy Management
CMH	High Yielding Canopy Management
CML	Low Nitrogen applied Canopy management
CMS	Standard Canopy management
CO2	Carbon di-Oxide
DEFRA	Department for Environment, Food & Rural Affairs
DM	Dry Matter
EPA	Environmental Protection Agency
EU	European Union
Expo	Exponential
FAO	Food and Agricuture Organization
FAOSTAT	The Food and Agriculture Organization Corporate Statistical Database
FI	Fractional Interception
FM	Fresh Matter
FNUpE	Fertilizer N uptake Efficiency
GAI	Green Area Index
GDD	Growing Degree Day
GHG	Green House Gas
GS	Growing Stage
HEAR	High erucic acid rape
HGCA	Home Grown Cereals Authority
HOLL	High oleic, low linolenic
HYLO	High Yield, Low Optima
INS	Indiginous Nitrogen Supply
IPCC	The Intergovernmental Panel on Climate Change
IR	Infra Red

KCL	Potassium Choloride
LAI	Leaf Area Index
LIN	Linear
N	Nitrogen (the symbol)
N2	Nitrogen (the molecule)
N2O	Nitrous oxide
NDVI	Normalized difference vegetation index
NH3	Ammonia
NH4	Ammonium
NNI	Nitrogen Nutrient Index
NO	Nitric oxide
NO2	Nitrogen dioxide
NO3	Nitrate
NUE	Nitrogen Use Efficiency
OJEC	Official Journal of the European Community
OM	Organic Matter
OSR	Oilseed Rape
PAI	Pod Area Index
PAR	Photosynthetic Active Radiation
PB	Paris Basin
PSNT	Pre-side-dress soil Nitrate Tests
RB209	Reference Book 209
REIP	Red Edge Inflection Point
RLD	Root Length Density
SAVI	Soil Adjusted Vegetation Index
SD	Sowing Date
SD1	First Sowing Date
SD2	Second Sowing Date
SD3	Third Sowing Date
SE	Standard Error
SI	Statatoury Instrument
SMN	Soil Mineral N
SNS	Soil Nitrogen Supply
SNUpE	Soil Nitrogen Uptake Efficiency
SOM	Soil Organic Matter
SS1-Com-R4	Sunscan Complete system with Radiation
UK	United Kingdom
USDA	United States Department of Agriculture.
WHO	World Health Organization
WOSR	Winter Oilseed Rape

Summary

Optimizing winter oilseed rape (WOSR) nitrogen management in mild Atlantic climate

Chapter 1- Introduction

Chapter 2- Literature Review

Chapter 3- The impact of sowing date on soil mineral nitrogen (N) uptake efficiency and fertilizer N uptake efficiency for winter oilseed rape (*Brassica napus* L.) in a mild climate

A three-year study on WOSR was carried out in Oak Park to determine soil N uptake efficiency (SNUpE) on unfertilized plots for Mid-Aug (SD1), End-Aug (SD2) and Mid-Sept (SD3) sowing dates. Fertilizer N uptake efficiency (FNUpE) was also studied on fertilized plots which were applied with various N rates; namely, Fixed 225 kgN/ha (generalized N rate advice based on soil N index system), UK-based canopy management (CM) N rates namely, CMStd= (Standard CM, which is based on crop N demand at flowering for an optimum canopy size); CMHiY= (canopy management for High Yielding crops with extra 60 kgN/ha than CMStd), and CMLo= (a lower predicted canopy size for a smaller N demand by flowering- applied on year 2 and year 3). Results demonstrated that SNUpE had a range of above 1 (or 100%) as a ratio of final N uptake to the spring soil N supply on all SDs. However, the extra values on earlier SDs were only slightly higher at 1.13 and 1.14 respectively. While on SD3 there appeared to be a higher SMN recovery of 1.68, this was significantly different across site-years. Also FNUpE increased by smaller N rate strategies and earlier sowing dates, and most varied through site-year interactions. Site-year 1 and 2 indicated a reduced value from the commonly assumed value of 60% in UK- CM. However, to demonstrate better clarification from FNUpE, values were regressed against yield and N rates for describing FNUpE according to the optimum N rate (Nopt). Then, based on the Nopt, FNUpEwas defined for each site-year and SD comparisons at the optimum economic yield .

Chapter 4- Nitrogen uptake to optimize canopy size and light interception for high yielding winter oilseed rape grown in a mild Atlantic climate

As a continuation of the previous chapter on the same plots, this chapter tested UK-CM principles on crop N demand at flowering and defined the optimum canopy size by using green area index (GAI). For this purpose, firstly it was essential to find the amount of crop N uptake for each unit of GAI. According to UK-CM, crops take up 50 kgN/ha/GAI, and GAI should be between 3 and 4 units, as the optimum value capable of intercepting 95% of fractional interception (FI) for achieving maximum yield. In this particular chapter, multiple linear and non-linear regressions were used to define the N uptake per unit of GAI and optimum values of GAI. Results demonstrated a 53.4 kgN/ha/GAI as a similar value to the UK-CM measured in Irish conditions in this study on flowering GS. Optimum GAI range was in a slightly wider range of 0.95 confidence interval than the UK assumption due to higher yield potential on these site-years, and variations caused by the late sowing date. Sowing date 1 and 2 had the optimum ranges of between 3.50 and 4.50, and SD3 had a wider range of up to5 units of GAI calculated as optimum. It was suggested that due to higher yield potential in the Irish climate, a wider range of GAI appeared to be optimum. Also, N rates from CMHiY, Fixed225 and CMStd were recorded within economical optimum N rates. Hence, based on economical and environmental concerns or individual farmer's targets for achieving a high yielding canopy size, various N rates can be selected.

Chapter 5- Understanding the impact of winter defoliation on crop N uptake and yield in a mild climatic condition on WOSR

On two site-years (2019 and 2020), and on the earlier SDs (SD1 and SD2, defined as one data set) zero-N crops by the means of a lawn mower were defoliated in January each year. One group of unfertilized defoliated plants were mowed with plant residuals removed from the plots (zero-Rm) and another group with retained (returned) plant residuals in the plots (zero-Rt) were compared to zero-Non (non-defoliated) crops in terms of their spring soil N supply, harvest N uptake, yield and yield components. Results demonstrated that plant debris from zero-Rt would not necessarily contribute significantly to an increase in harvest N uptake on these plots (except in one year). Also, harvest N uptake was shown to be numerically higher in Zero-Non than defoliated plots. To determine if winter cut plots need additional N application, seed yield of fertilized and defoliated (zero-Rm) crops were compared to fertilized, non-defoliated crops through regression analysis with N rates. Results demonstrated a higher fertilizer application is needed on defoliated plots. In 2019, the extra-required N fertilizer was calculated as 47 kgN/ha when 44% of vegetation was removed in winter. In this year, for each 1 kgN/ha of vegetation loss in early spring, an extra N application of 3kgN/ha was required to avoid yield penalty. In 2020, there was a yield reduction of approximately 0.5 t/ha on zero-Rm fertilized crops compared to non-defoliated ones, in spite of their similar Nopt. Based on UK-CM principles, theoretically an additional 30 kgN/ha could compensate for each 0.5 t/ha of yield loss.

Chapter 6- Overall discussion

Chapter 7- Overall conclusion

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1.0. Introduction

The application of fertilizer nitrogen (N) to winter oilseed rape in Ireland has to date largely been based on soil index systems gathered as the Statutory Instrument (SI) 605 (2017) regulations to meet the EU Nitrates directive. According to these regulations, it is mainly the crop history of the field, with no consideration of crop N demand, which determines the recommended level of fertilizer N to be applied. A previous study in the maritime climate of Ireland by Walsh (2016) showed that the soil N index system, based on the previous crop history, was only able to determine 20% of the variations in N supply across different 110 sites, during three years 2012 to 2014 in Ireland.. Apart from this reliance on a single imprecise factor, there is a necessity for environmental and economic reasons to develop more precise N recommendation systems. The prices of fertilizers namely, CAN 27%, surged more than three times in one year, from €235/ha in 2021 to €720/ha in 2022 (by April) with limited availability according to Teagasc Publication 2022 (available at www.teagasc.ie/publications/2022/high-fertiliser-prices-where-to-now.php). Moreover, Ireland`s GHG emission proportion is the highest in the EU, in terms of the agriculture activities including high level of methane and nitrous oxide according to the IPCC (2021). Increasing numbers of dairy cows and N fertilizer use (Lanigan *et al.*, 2018) are the examples of main sources of GHG emissions. To stimulate a change, EU policy is targeting a reduction in fertilizer use on farms (EU Farm2Fork regulation policy) to support growers who are adopting crop rotations that include broadleaf crops. Winter OSR grown in rotations is able to break the life cycle of disease, pest, and weeds associated with cereals and contribute to the cereal yield increase even in short rotations (Hegewald *et al.*, 2018). There is relatively little WOSR grown in Ireland currently (6,500 ha) (Central Statistics Office, 2020), andthe plant is adaptable to Ireland's soils and maritime climate as there is also a viable international market for oil and protein cake (CROPQUEST report, Teagasc.ie).

To overcome the lack of precision in N application due to generalized advice based on one-size-fits-all current N prediction rules, an understanding of plant N demand, soil N supply and N fertilizer use efficiency is required (Appel, 1994). In the case of WOSR, these principles are not straightforward to determine, because the plant: a) is able to uptake substantial amount of N from soil over autumn and winter, b) reaches the critical stage of flowering, at which radiation interception beneath the crop is a limiting factor, c) uses N less efficiently as a general concept compared to cereals by relocating N from vegetative parts to pods and seeds (Lunn *et al.*, 2001).

The developed system of N prediction in the UK is based on a target yield and largely quantifies crop N demand according to the canopy size at the critical growth stage of flowering (Sylvester-Bradley *et al.*, 1998). A canopy of 3.5 units of green area index (GAI) is assumed to be the optimum size at flowering, and that each unit of GAI contains 50 kgN/ha; hence 175 kg N is estimated to be the N requirement by flowering. Secondly, a summation of crop N content and SMN in early spring is known as soil N supply, and can be measured prior to N fertilizer application. It is assumed that the plant can take up and use soil mineral N with 100% efficiency. Thirdly, fertilizer N uptake efficiency (FNUpE %) for which there are considerable variations, is 60% on most soil types in the UK climate. These three principles underpin the current UK "Canopy Management" (UK-CM) approach to N management in WOSR. This N prediction system on WOSR is summarized in AHDB Nutrient Management Guide (RB209) (www.AHDB.org.uk), which firstly was tested on cereals (Sylvester-Bradley *et al.*, 1998) and then was carried out on WOSR later (Berry *et al.*, 2011; Berry and Spink, 2009; Lunn *et al.*, 2001).

Prediction of N based on WOSR ability of N uptake both at the end of autumn and winter has broadly been studied in French and German literature with a consideration of their continental climate with cold winters, warmer spring and summers (Dejoux *et al.*, 2000; Sieling *et* *al*., 2017). Identification of the climate difference among regions was followed by the updated world Köppen- Geiger climate classification map (Peel *et al*., 2007). Based on this climate regionalization, Ireland's mild climate that is dominated by Atlantic maritime air masses, is in the same category of the UK's climate rather than other European countries. However, , assessing the suitability of the UK-CM approach for determining N application is yet to be tested as initial steps for developing a more precise approach than the generalized N application scales in Ireland. Long-term meteorological studies show that in the northeast and southeast of the UK, where WOSR is grown, there are colder winters and hotter summers with less rain over autumn due to the influence of warm continental polar air masses. In contrast, Ireland is influenced by mild Atlantic polar air masses, which frequently cover the land, with higher precipitation during autumn, milder winters, unstable rainfall pattern and cloud cover compared to the UK. Hence, it is important to consider if milder winters (often with insignificant winter frost) would result in higher post winter biomass and N uptake. Moreover as sowing date can be interrupted by poor weather conditions and also given that crops can be damaged by pigeon grazing, it is important to determine if small post-winter canopies would result in higher crop N demand in order to avoid the yield penalty. Therefore, it is important to prove if early spring soil N supply measurement can be an accurate scale of final (harvest) N uptake on different canopy sizes.

Larger canopies at flowering (i.e. due to early sowing date) do not necessarily produce higher yields (Spink *et al*., 2002), hence, identifying the optimum canopy size which provides adequate green area for photosynthesis and avoids self-shading or lodging, is unknown in the mild climate. There has also been a possibility for additionally available N (AAN) release between spring and harvest due to the favourable soil/weather conditions between spring (after spring sampling) and harvest on unfertilized plots. From the outline above, over-using N fertilization specifically on WOSR, with less physiological-agronomical knowledge mainly on mild climate, is quite probable. Hence, the specific knowledge gaps as per below will be tested in this project, both as a novel site-year specific study, for a potential comparison to the UK-CM and continental systems of N fertilizer applications. Therefore, this study will test:

- Soil N uptake efficiency
- Fertilizer N uptake efficiency
- Crop N demand for each unit of GAI
- Optimum GAI units for intercepting light at flowering
- Optimum GAI units for yield formation at flowering
- Higher N requirement on the lost vegetation in spring due to defoliation

These will be examined so as to bridge the gap between a more precise N strategy and a reduction of N losses. This thesis addresses these aims in the chapters as set out below:

Chapter 2- Literature review

Chapter 3- The impact of sowing date on soil mineral N uptake efficiency and fertilizer N uptake for winter oilseed rape (*Brassica napus* L.) in a mild climate

Chapter 4- Nitrogen uptake to optimize canopy size and light interception for high yielding winter oilseed rape (*Brassica napus* L.) grown in a mild Atlantic climate

Chapter 5- Understanding the impact of winter defoliation on crop N uptake and yield in a mild climatic condition on WOSR

Chapter 6 and 7- Overall discussion and conclusion

2.0. Literature Review

2.1. Oilseed Rape in a global context

2.1.1. History and Taxonomy

According to Indian Sanskrit from about 1500 B.C., *Brassica* species were well recognized for their medicinal purposes, as a green vegetable or as condiment mustard. The earliest account of rapeseed cultivation in Europe dates from 1570, when winter oilseed rape was grown in the Rhineland area of Germany as a cheaper substitute for olive oil in lamps or as a cooking fat (Heresbach, 1570). Later, when steam engines were invented, *Brassica* oil, with high erucic acid content was used as lubricating oil for water-washed parts and remained so until after World War II (National Research Council of Canada, 1992). The Brassicaceae family (formerly Cruciferae) has 375 genera and 3200 species. The genus *Brassica* consists of about 100 species including *Brassicae napus* L., subsp. *oleifera* mainly known as oilseed rape, rapeseed, or canola. As there is no known wild form of *Brassica napus* L., it is therefore believed this species originated from a cross between two diploid maternal donors *B. rapa* L. (syn *B. campestris*, turnip, field mustard) and *B. oleraceae* L. (Brassica vegetables). The taxonomic relationship among *Brassica* species is shown in the Triangle of 'U' (Nagaharu and Nagaharu, 1935) (Fig 2-1). Widely cultivated species are *B. nigra* Koch (black mustard), *B. napus* L. (oilseed rape), *B. carinata* Braun (Ethiopian mustard), and *B. juncea* (Indian mustard). The three species with higher chromosome numbers, namely, *B. napus*, *B. juncea*, and *B. carinata* are derived from the diploid species: *B. nigra*, *B.rapa*, and *B. oleracea.*This natural hybridization event in case of *B. napus* L., subsp. *Oleifera* occurred between *B.rapa* (AA. 2n=2x=20) and *B.oleracea* (CC, 2n= 2x=18), made the *B. napus* an allotetraploid genome composition (AACC, 2n=4x=38) (Nagaharu and Nagaharu, 1935).

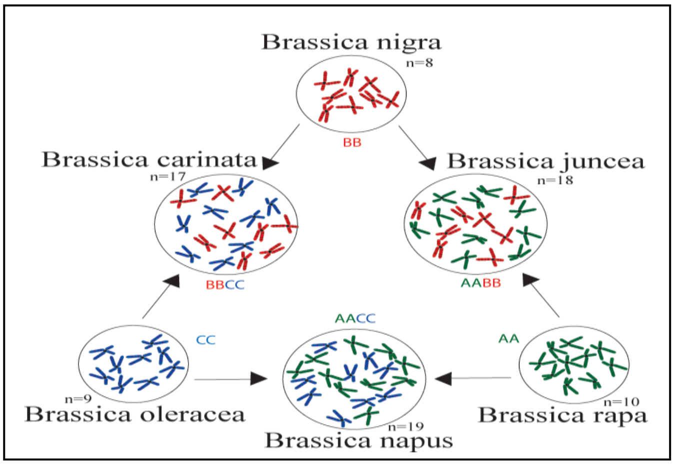


Figure 2.1. Triangle U: Relationships between the main Brassica species (Nagaharu and Nagaharu, 1935)

2.1.2. Production areas and climate

A switch to edible oilseed production since the 1970s resulted in enhancing areas for rape-seed production in Asia by 70%, and by 40% in Europe and Canada by the 1990s. Other uses include biofuel and industrial products, with the remaining seed materials (meal) used in animal feed for its high protein content, residual oil, and fibre.

Rapeseed growing areas of the world include wide variation adaptations mainly due to its gradual planting optimization and breeding improvements (Beres, *et al*., 2019). A wide range of climate conditions, i.e. from western Canada to India and South Australia, shows a range for the crop to grow (Mendham and Salisbury, 1995). However, winter endurance is a predeter-mine factor for the crop survival under unfavourable winter conditions. In this condition the crop usually will be differentiated but not completely so as to be able to change the vegetative phase into generative later during growing season. Cells in winter hardiness are rich in soluble carbohydrates (Gavaliene *et al*., 1998), act as “anti-freeze for cars”, avoiding the crop damage during winter. Also, if the growth in autumn is not enough: 3-4 leaves formed and 3-5 mm thick root collar (Diepenbroke and Grosse, 1995) there will not be enough accumulation of cellular sugar and amino acids, therefore, there will be a danger of not withstanding winter frosts (Morris,1996). Hence, plants winter hardiness expose during the cold acclimatization period (Lääniste, *et al*., 2007). Therefore, there is a category based on which major global production systems are determined according to the phenology and seasonal fit for better growth adaptation (such as vernalization requirement) : 1) autumn-sown OSR mainly in EU, China and USA where crops have longer vegetation phase during winter, which may include dormancy in colder regions. Stem elongation corresponds with springtime and harvest is in summer. Winter hardiness, frost damage, establishment and survival are the main concerns in these areas. 2) Spring OSR varieties, with short growing seasons in higher latitudes and altitudes, such as Canada; these varieties have no requirement for vernalization, the crop growth cycle is shortened and yield is more limited. However, Canadian canola yield increased by 50% between 2000 and 2013 as the result of new higher yielding hybrid varieties and herbicide tolerance, together with a switch to minimum tillage (Morrison *et al.*, 2016). 3) Spring OSR cultivars sown in autumn in lower latitudes as India, Australia and South America; these cultivars sown in autumn, grow in mild winter and are harvested in early summer before the beginning of heat and drought (Kirkegaard *et al.*, 2020). The average yield is approximately 1.4 t/ha in Australia where yield is considered to be water-limited to 42 – 68% of its potential (yieldgapaustralia.com.au). Current research focus in Australia is to identify the optimum flowering time, sowing date, and varieties of suitable phenology (Lilley *et al.*, 2019). Table 2.1 is a summary of the average production (tonnes) of both spring and winter oilseed rape varieties together with the related areas of cultivation (ha) and yield (t/ha) from the year 2000 to 2018 in different regions (FAOSTAT, 2020).

Table 2.1. Annual average of oilseed rape production, area of cultivation and yield from 2000 to 2018

	Production (tonnes$\times 10^3$**)**	**Area of cultivation (ha**$\times 10^3$**)**	**Yield (t/ha)**
Canada	12,668	6,660	1.90
China	12,711	6,977	1.82
EU(except Poland) (27)	15,964	5,118	3.11
India	6,734	6,014	1.11
Poland	1,946	722	2.69
Other countries	7,029	5,047	1.39
Total	57,051	30,540	1.86

Source: FAOSTAT, 2020

2.1.3. Production changes over time

WOSR production increased annually by 10-14 Mt of plant protein together with 20-30 Mt of oil (Wanasundara *et al.*, 2016). The quality of oil and meal has improved over the last 60 years. High levels of erucic acid in the oil, which brought heart disease in animals, were of concern in the past (Gunstone, 2004). This limited its use as a food/feed, hence, breeding programs in 1960s led to lessen the production of unfavourable glucosinolates and fatty acids. *Brassicae napus*, *B. rapa* and *B. juncea* varieties were manipulated and branded as 'double-low' varieties. Canola is the name of the double-low trademark, largely used in Canada, USA and Australia which denotes that the variety has <2% erucic acid in the oil, and <30 µM/g glucosinolates in the meal (Gunstone, 2004). Also, progressive breeding programs and more advanced agronomic practices have increased the yield potential of *B. napus* winter varieties, which comprises the most common rapeseed globally. According to Figure 2-2, the crop has had an upward trend in terms of both production tonnes (t) and world harvested area (ha) during the last 23 years (FAOstat, 2020). Production has tripled since 1994 from roughly 25 to more than 75 million (M) tonnes in 2017. Similarly, the cultivated area increased from 20 M ha to nearly 35 Mha.

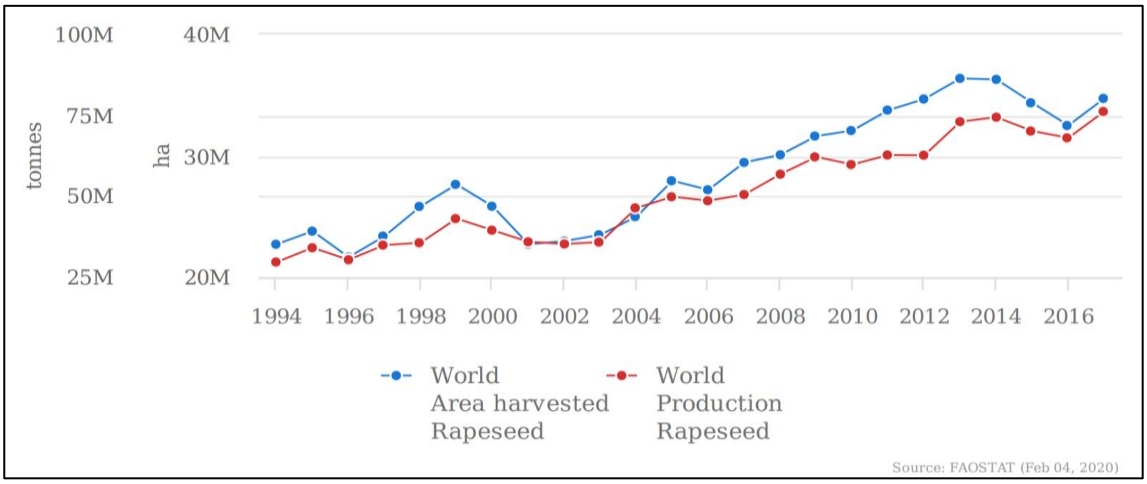


Figure 2.2. Production and yield quantities of Oilseed Rape in the world from 1994 to 2017 (Source: FAOStat, 2020)

Among EU countries, France and Germany are the largest producers. In 2018 for instance, the harvested areas were respectively 1,615,522 ha and 1,224,400 ha. Next, Poland with 845,110 ha, and the UK 583,000 ha. As a world scale, China and Canada had a 2- and 3-fold increase, respectively since 1993 in their annual production (Kirkegaard *et al.*, 2020).

B. napus L. is the second largest oilseed produced worldwide (USDA, 2022). In terms of oil consumption, OSR is the third highest (27%) after palm (64%) and soybean oil (52%) (USDA, 2020) (Figure 2-3).

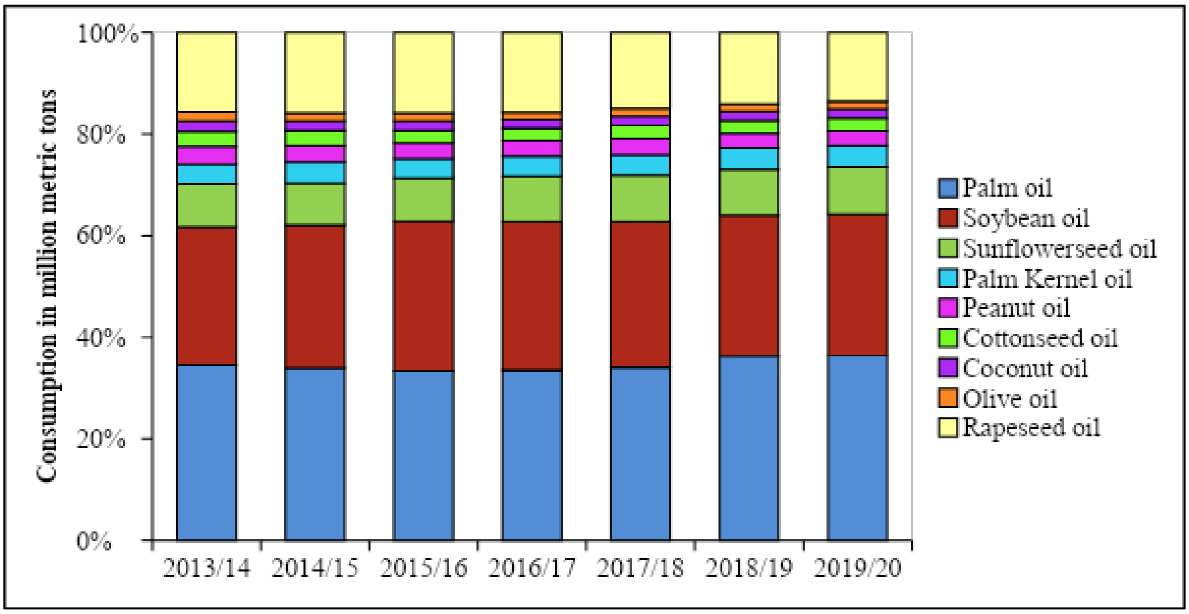


Figure 2.3. World oil-consumption rate (Source: USDA, 2020)

The primary use of *B. napus* is as an oilseed, its secondary product is a high-protein meal with high potentials to be used as plant-based protein source (Ammeter, et al., 2021).

2.1.4. Oilseed rape other benefits

Numerous studies have shown that including OSR in rotation with cereals, results in an increase in cereal`s yield, due to breaking the soil-borne and foliar- pathogen cycles (Kirkegaard *et al.*, 2008). Almost twenty years ago, it was recommended to grow WOSR once in every four years to reduce pests, disease, weed problems and associated yield loss (West *et al.*, 2001). However, market demand or government incentives and progress in varietal re-sistance have made intensified cultivation for shorter rotations possible (Kirkegaard *et al.*, 2020). The range and severity of the pathogens vary regionally and seasonally (Kirkegaard *et al.*, 2008). The main concern of short rotation is mainly related to diseases such as Blackleg (*Leptosphearia maculans*) and Clubroot (*Plasmodiaphora brassicacea*), or increasing resistance to herbicides (Heap and Duke, 2018), and fungicides (Van de Wouw *et al.*, 2017).

The production areas of OSR have doubled since the 1990s, while the total farming area has remained constant in the main production regions (FAOStat, 2019). This means, WOSR is grown in even more intensive and shorter rotations than before (Hartman, 2012; Hegewald *et al.*, 2018; Sprague *et al.*, 2006). In Ireland, according to the Central Statistics Office (2018), OSR, beans and pea rotation crops accounts for 7.12% of the arable areas, therefore, continuous cereal production seems to be a common practice. A study compared a 5-year break crop rotation with a 3-year cereal rotation, and two monocultures of spring barley and winter wheat from 2004 to 2010 in the southeast of Ireland. Results showed that “crops in rotation with spring oilseed rape and beans provided better yields and higher profit margins than monocultures, or with those of suboptimal rotations” (Forristal and Grant, 2011). Yield of OSR have been found to increase by 0.22 t/ha after barley and 0.46 t/ha after legumes and with an intermediate increase after wheat (Kirkegaard *et al.*, 2020). In many cases, the rotational effects are attributed to nitrogen (N) or water supply, mainly because legumes in the crop sequence contribute residual N or water.

Generally, productivity improvement requires a balance among sufficiently diverse rotations, the use of resistance cultivars, and of agricultural inputs and the avoidance of resistance build-up (Hegewald *et al.*, 2018).

2.2. The main production challenges

2.2.1. Establishment

Establishment, as a definition, is an accumulation of three stages: sowing to germination, germination to emergence, and emergence to establishment (McWilliam *et al.*, 1995). The main production challenge for winter oilseed rape is related to the short working window for seedbed preparation between cereal harvest and the optimum drilling period during August and mid-September. In maritime climates, this problem is more significant, especially the risk of delayed autumn sowing (e.g. mid-September) due to higher precipitation. It has been reported that in some years, from September to February, the risk of poor establishment was so considerable that 30% of crops were abandoned in the eastern part of the UK where OSR is mostly grown (McWilliam *et al.*, 1998). This can be as the result of physical, mechanical, chemical, and biotic factors (e.g. pests, disease, pigeon damage, etc.) either as single or interactive effects. Physical factors forming the quality of the seedbed are mainly comprised of soil texture and stability, cultivation method and a seedbed structure. Water supply, temperature, oxygen, depth of sowing, herbicide residues, pH, fertilizers, and crop residues are all factors that affect establishment.

An ideal seedbed structure is a tilth with an even, fine surface and a well fissured underlying structure (Håkansson and von Polgár, 1984). The firm bottom layer helps control drilling depth and water transfer through capillary movement with the fine texture on top which improves seed/soil contact, reduces evaporative losses, and facilitates considerable root growth (McWilliam *et al.*, 1998).

There are several methods of crop establishment possible for oilseed rape growers depending on machinery and labour availability and cost targets. Soil management strategies such as minimizing compaction and preserving high organic matter, and selecting an appropriate drilling method are important (McWilliam *et al.*, 1995). Strip-till (ST) drilling as a form of conservation tillage may reduce tillage cost and protect soil from erosion and disturbance when compared with conventional tillage, and this has been proved as a benefit to *Brassica* (Haramoto and Brainard, 2012).

Brassica seeds can tolerate a pH range from 5.5 to 8.0 and prefer a fine, firm, and moist seedbed structure (Almond *et al.*, 1984). The speed of germination in rapeseeds responds to soil temperature which varies from 1 day at 21°C to 25°C to 11-14 days at 2°C (Kondra *et al.*, 1983). Another factor, influencing establishment is related to soil moisture during autumn. Date of sowing is different based on the onset of winter and latitude (Walker and Booth, 2001). In the continental part of Europe, for instance, late August is the preferred timing to ensure there is sufficient crop growth to tolerate the winter frosts, while in an Atlantic maritime climate, cultivation can be delayed until early to mid- September (Walker and Booth, 2001). Delayed sowing date in these conditions can be compensated for by increasing seed rate according to the AHDB Nutrient Management Guide (RB209) (www.AHDB.org.UK). Yet, there are reports showing similar yields achieved from a wide range of seed population rates on winter oilseed rape (McWilliam *et al.*, 1995), because high seed rate results in high plant population and greater competition for early crop development that leads to tall and thin stems prone to lodging before harvest. On the contrary, low plant population due to low seed rate causes an open crop canopy structure, which is shorter, thick-stemmed, with more branches causing delayed maturity (Walker and Booth, 2001). A plant population of 40 seeds/m^2 can result in comparable seed yield in UK studies (Walker and Booth, 2001).

2.2.2. Environmental issues associated with N cycle

Nitrogen availability strongly determines plant growth and productivity. Several forms of N in natural soils are in inorganic forms, such as nitrate (NO_3^-), nitrite (NO_2^-) and ammonium (NH_4^+). Mainly nitrate is a major form of N in aerated soils, whereas ammonium can be a more common form in acidic soils/ anaerobic environments (Miller and Cramer, 2004). Nitrite availability varies depending on the balance of nitrification: denitrification worldwide, considering the concentration of the molecule is generally lower than that of nitrate and ammonium (Shen *et al.*, 2003; Kotur *et al.*, 2013). By any means, the N element is the most limiting nutrient, for which plant growth is often limited by their availability in natural environments. To increase N absorption, plants have developed a transport and signalling mechanism to their N sources (Kiba and Krapp, 2016). Nitrate and ammonium are mainly present in natural croplands at higher concentration (Miller and Cramer, 2004), while nitrate is a more preferable form of N absorption due to its local and systemic signal that regulates a wide range of gene expressions (Ho *et al*., 2009; O`Brian *et al*., 2016); from seed dormancy (Alboresi *et al*., 2005) to floral induction (Castro Marín *et al*., 2011).

The amino-N released by proteolysis from decaying plant or animal matter is first degraded to NH_4^+. In soils or waters with a neutral to basic pH, the NH_4^+ then becomes oxidised to NO_3^- by several steps, each depending on specific types of microorganisms. This conversion process can cope with relatively large amounts of NH_4^+, as much analysis of agricultural systems has shown: within just a few weeks after the addition of an NH_4^+ fertilizer, the free NH_4^+ concentration in the soil solution is diminished to a very low level (de Willigen, 1986). However, because nitrifying bacteria do not successfully colonize acidic soils, most of the N released from the turnover of organic matter in such soils may remain as NH_4^+. Because the research literature has been so dominated by the mineral nutrition of agricultural plants of temperate or sub-tropical origin, N nutrition is often discussed as if NO_3^- were the only significant source of N (Forde and Clarkson 1999). From an ecological aspect, and considering the large areas of acidic soils, many take a different view and emphasise our comparative ignorance of the factors regulating NH_4^+ nutrition (Alexander, 1983). Hence, in the current literature review, available source of N (ammonium or nitrate) are mentioned based on the specific literature.

The main sources of N in agriculture come from industrialized fertilizers (through Haber Bosch process) as well as soil mineralization and N fixation process, but N is vulnerable to lose through volatilization, denitrification, and leaching.

Depending on the soil type, there is 2,000 to 12,000 kgN/ha in the top 15 cm of soil. This comes mainly in four forms: 1- organic matters (plant materials, fungi and humus), 2- (micro) organisms, 3- ammonium ions (NH_4^+) which are trapped by clay (-) soil particles, and 4- mineral N in soil solutions NH_4^+, NO_3^-, NO_2^- (Cameron *et al.*, 2013). Figure 2-4 shows the adds-in, losses and transformation of N within the soil/plant cycle, in which the transfer of N to a wider environment can happen (Cameron *et al.*, 2013).

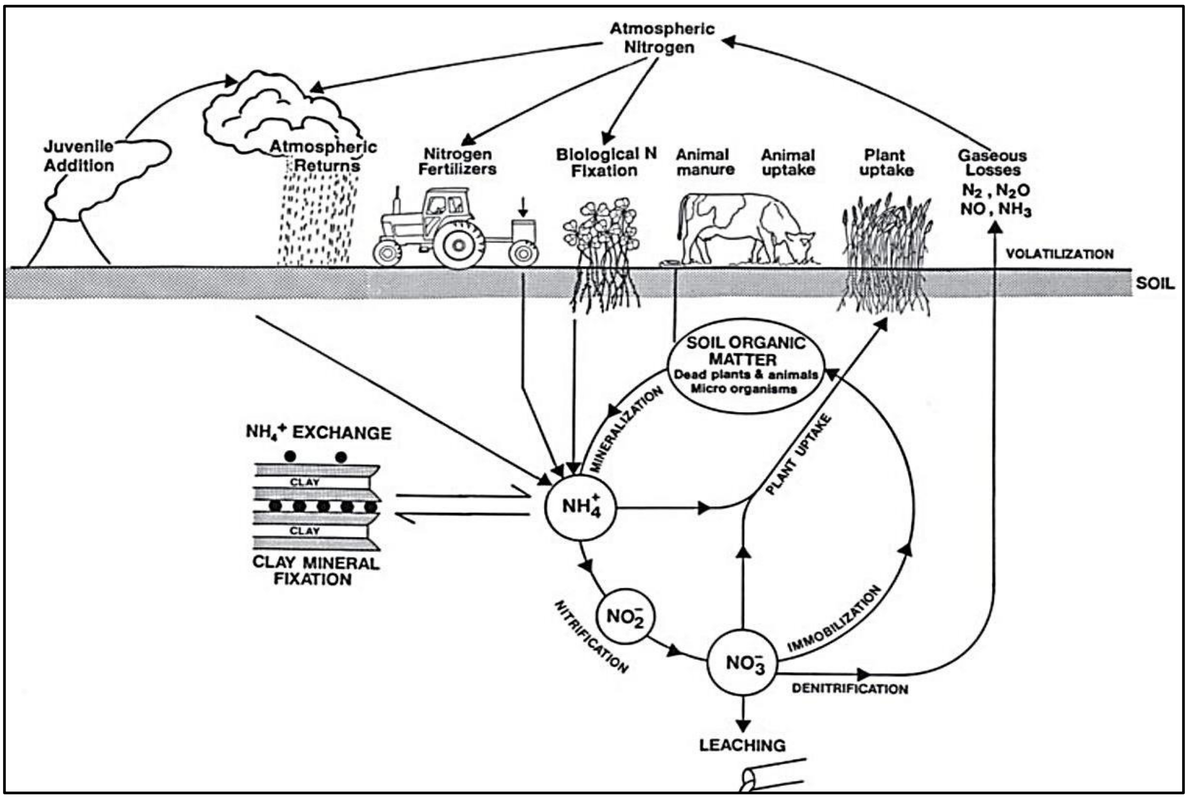


Figure 2.4. Soil, plant, and environmental N cycle (Taken from: Cameron *et al.*, 2013)

2.2.2.1 Mineralization and available N

Mineralization is a conversion of organic N into inorganic forms of ammonium (NH_4^+) and NO_3^- (nitrate), so as to be in an available form for plant N uptake mainly by the help of microflora and fauna. Yet, these ions are prone to N loss through ammonia volatilization NH_3^+ (g), leaching (through drainage water) and denitrification (NO_3^- transformation into e.g. NO_x gas forms), although, atmospheric depositions can return NH_4^+ to the soil (Figure 2.4).

Mineralization from crop residues depends on the quantity of C:N ratio, which needs to be balanced. For example, large amounts of lignin or hemicellulose as the source of C might reduce the rate of mineralization (Honeycutt *et al.*, 1993). Hence, the addition of organic matter with low C:N (<25) induces net N mineralization (Hadas *et al.*, 2004), while any amendment with high C:N (>25) organic material leads to net N immobilization (Moritsuka *et al.*, 2004).

Generally, the source for plant available N includes both organic and inorganic N pools. The inorganic N pool is mostly ammonium, and can volatilize if surface applied, because following oxidation from ammonium to nitrate, become at risk from leaching and denitrification process, hence the plant N availability will be reduced (Stein *et al.*, 1995). The organic pool, however, consists of larger groups of organic compounds from which ammonium is decomposed at various rates. This decomposition is assumed to happen by slow or rapid fractions depending on soil and weather conditions (Gilmour, 1998). Therefore, the plant available N is "an accumulation of the portion of the initial ammonium that does not volatilize, plus the organic N that is mineralized in a period of time" (Gilmour and Skinner, 1999). Depending on the incubation conditions, plant N uptake can be less than the available N pool, because uptake relies on the availability of ammonium and/or nitrate when no loss mechanisms occurs and also N uptake efficiency of the specific crops (Gilmour *et al.*, 1996).

Predicting the availability of N for plants at a given time period is difficult as it depends on the decomposable materials and site characteristics (Stein *et al.*, 1995). Moreover, organic N, inorganic N and decomposition kinetic ranges vary and are dependent on soil temperature and moisture which affect the rate of decomposition and net N mineralization (Gilmour, 1998; Terry *et al.*, 1979). The most accurate plant available N estimation is based on statistical relationships between C and N; for example, net N mineralization is directly related to the crude protein content of biosolids (Hattori and Mukai, 1986).

Depending on soil conditions, two important mechanisms: diffusion and mass flow, explain the movement of decomposed materials at the root surface. Volumetric water content, bulk density and buffering power are responsible for up to 50% of the total nitrate transported to the root surface by diffusion (Jungk and Claassen, 1997; Strebel and Duynisveld, 1989). Moreover, the charge of the nutrient ion and the ion exchanging capacity of soil N forms such as amino acids, adsorbing to the soil matrix are equally important (Li *et al.*, 2010a). Some studies aimed to estimate soil N supply based on the parameters above, but, due to its complex nature, other studies were needed to validate the models (Inselsbacher and Näsholm, 2012; Jungk and Claassen, 1997).

Soil temperature is a driving factor for diffuse fluxes for the availability of plant nutrients, in such a way that any temperature change affects diffuse fluxes directly and indirectly by altering the viscosity of the soil solution (Inselsbacher and Näsholm, 2012; Kelly and Mays, 1999). Studies showed that organic N contributes to the total supply of N for plant uptake via diffusion mechanisms even at lower soil temperature, but as the temperature increases, smaller N-compounds become more available than larger compounds (Inselsbacher and Näsholm, 2012).

With a better understanding of N mineralization and plant N availability, a more precise quantitative system of N prediction could be built up for future fertilizer advice which incorporates minimizing nitrate leaching and other losses (Shepherd et al., 1996) using model studies where mineralization can be quantified (Powlson et al., 1994; Shepherd et al., 1996). To quantify SMN, a German metrological website Deutschland Weather Service (DWD) takes evaporation of water in the soil into account and tailors it to the Kersebaum (2007) nitrogen model. This model calculates the crop specific potential evapotranspiration from daily weather data, so that, a daily net mineralization of simulated nitrogen- as a function of temperature and soil moisture content- is calculated from the decomposable nitrogen (Richter et al., 1982). In fact, based on the given initial Nmin method (will be discussed in 2.6), the calculated soil moisture on the day after harvest and the further movement of transferred soil water will be taken into account for estimating mineralization rate. Moreover, in French studies, CERES-rape model was developed as a simulation of growth and development. The model included variables such as soil components, net photosynthesis, leaf area index, nitrogen uptake, partitioning of C and N, and grain filling under the effect of crop N status based on daily weather data (rain, air temperature and solar radiation) to account for N limitation (Gabrielle, 1998 a,b).

2.2.2.2 Nitrate Leaching

In Ireland, chemical N fertilizer use increased by 5% between 2012 and 2015 in comparison with 2008-2011, yet monitoring stations for groundwater showed the mean nitrate concentration has remained <50 mg/l. Eighty-seven percent of these stations had mean nitrate value <25 mg/l. Also, for surface water, nitrate measurement was <40 mg/l (Council of the European Communities, 2018), which means Ireland was at no risk of nitrate pollution at that time scale.

Application of N fertilizers is decided according to evidence-based advice, with the maximum allowable amounts incorporated, as a part of European Union Water Framework Directive to protect water sources, implemented under Statutory Instruments (S.I. No. 605, 2017) for Good Agricultural Practice for Protection of Waters. In this regulation, nutrients are limited based on an index system determined by previous cropping history and yields. Noticeably, the implementation of the Nitrate Directives seems to be a one- size-fits-all approach, which fails to differentiate the importance of site and year specifics (Buckley and Carney, 2013). Depending on nitrate containment, nitrification or denitrification rate, and the drainage of the field, over a certain period of time, leaching occurs differently (Cameron *et al.*, 2013). Leaching also strongly depends on soil water storage capacity (Cameron *et al.*, 2013). In regions with high precipitation rates, nitrate as a mobile ion tends to be washed out from the sandy, free-draining soils through the soil profile (Humphreys, 2007). Because of leaching, soil fertility reduces and the risk of environmental pollution increases (WHO, 1993; Wild and Cameron, 1980). Recently a model-based study on oilseed rape has shown that N leaching is site-specific and increases under the influence of fertilizer amount and its type (Räbiger *et al.*, 2020). As the consequence of leaching, oxygen depletion due to algal bloom formation occurs which then leads to fish loss and pollution due to eutrophication (Smith and Schindler, 2009).

2.2.2.3 Denitrification

Denitrification occurs in poorly drained, heavy, or aggregated soils with high precipitation. In anaerobic saturated soil conditions, nitrate (NO_3^-), instead of oxygen, is used during respiration of denitrifying bacteria, consequently, nitrite (NO_2^-), nitric oxide (NO), nitrous oxide (N_2O), and finally N_2 (dinitrogen) are released. It is believed that the most common pathway for N loss in Irish fields is attributed to denitrification process (Humphreys, 2007). The annual average rainfall is 1000 mm in the east side of the country with arable lands, with respectively, autumn, winter, and spring having the highest level of precipitation and evapotranspiration of 450 mm per year. Subsequently, this process leaves a surplus of 550 mm per year between the months of October and January. In this scenario, nitrate loss through leaching and denitrification is more probable (Humphreys, 2007).

2.2.2.4 Volatilization

Ammonia (NH_3^+) volatilization is the loss of N from the soil/plant cycle which may later be returned from the atmosphere to the earth`s surface (i.e. through rainfall) resulting in acidification and eutrophication. Ammonia emission is also considered as an indirect source of nitrous oxide greenhouse (GHG), and the agriculture sector comprises 50% share of all volatilized NH_3^+ worldwide. Application of non-protected urea fertilizers, as an example, contributes to the risk of volatilization depending on soil climate conditions (Sommer *et al.*, 2004).

Nitrous oxide (N_2O), the fourth largest contributor to the greenhouse effect, can be driven by warm and wet anaerobic soil conditions with high content of available C and N to produce higher emissions. The sources of N_2O can both be anthropogenic and natural; however, the former is of greater concern for GHG in the atmosphere. If Calcium Ammonium Nitrate (CAN 27%) is the preferable type of N fertilizer, in mild, wet climates on high organic soils, the direct N_2O emission factor (EF) averaged 1.49% on Irish grasslands, with a wide range of variation from 0.58% to 3.81% (Harty *et al.*, 2016). This is while the IPCC default EF for N_2O emission is 1% of the applied N, regardless of its form (IPCC, 2014). Hence, it seems that the necessity of managing N fertilizer application is significant in terms of both minimizing environmental impact and maximizing economic returns.

Ireland so far possess the highest share of non-CO_2 GHG emissions resulting from agricultural activities: about 50% of the GHGs is related to methane (CH_4) and nitrous oxide (N_2O) (IPCC, 2021). Based on the reports, GHGs in this country have been increased by 3.8% from 2005 to 2019 (EPA, 2020). Therefore, it seems without taking force majeure mitigation actions, GHG from this sector will be increased by 9% in 2030 from available figures since 2005 (Läpple *et al.*, 2022), where notable, the increase is mainly associated with increasing dairy cows and N fertilizer use (Lanigan *et al.*, 2018).

Brassica napus is the major oil crop for producing biofuels in Europe (Hamelinck *et al.*, 2013) and it can predominantly be a GHG producer through its high N demand (Borzęcka-Walker *et al.*, 2011) by increasing gaseous N_2O from agricultural soils (Stehfest and Bouwman, 2006) or N surpluses (=N fertilization- N removal) in arable lands (Van Groenigen *et al.*, 2004). Considering the global warming effect of N_2O, a reliable emission factor for calculating GHG balances of OSR production was studied by Ruser *et al.* (2017) in Germany which showed that N fertilization of 240 kgN/ha had the highest value of N_2O emissions. It was also shown that oil yield increased up to an application rate of 120 kgN/ha, but remained constant at higher N fertilization. Emission increased exponentially with surplus N applications, therefore, it was concluded that reducing N rate would directly affect mitigation of GHG emissions (Ruser *et al.*, 2017).

2.2.2.5 Carbon footprint

Climate-change studies consider future crop yields in combination with climate scenarios using crop models calibrated to respond to the changes in a specific temperature and rainfall pattern (Kirkegaard *et al.*, 2021). Currently, studies associated with CO_2, temperature and water supply are restricted to pot experiments, suggesting that yield increases related to increased CO_2 are not able to offset the negative effects of drought and temperature and are variety-specific (Frenck *et al.*, 2011). A study on the statistical models related to the observed yield and weather from 1974 to 2013 from 20,000 political units was conducted to predict the probable impact of current climate change on *B. napus* plants (Ray *et al.*, 2019). The global units for OSR cultivation were summarized as Europe, Canada, China, India and Australia. The study suggested climate change may already affect OSR production with a projection of yield reduction mainly in Western and Southern Europe, Central and Eastern Asia, and Northern Europe, respectively with larger scales than for Northern and Central America, Southern Asia and Australia regions.

2.2.3. Nutrient requirement

Fertilization practices need to be determined according to soil and crop analyses so as to define the related soil index for each element. However, in maritime climatic conditions where acidic soil is dominant, liming requirement should be determined prior to further fertilization decisions (Haynes, 1982). Other elements such as phosphorus (P), potassium (K) and magnesium (Mg) tend to be less mobile in the soil and there are large reserves of these nutrients in most soils; but the availability of each to the crop needs to be decided as soil nutrient indices, according to the AHDB Nutrient Management Guide (RB209).

Other elements can also impact on growth, for example, Boron (B) deficiency might result in stunting with brittle petiols, poor seed set, and a reduction in seed number per pod and seed weight, showing it to be an important micronutrient element. This might be attributed to high pH soil (over-liming) or light textured soils, and can be rectified by foliar application at the onset of spring growth (Wall and Plunkett, 2016).

The annual application of N and sulphur (S) are the two most demanding elements on all oilseeds for which the applied amounts can be determined according to measurements of the soil and crop (Nutrient management guide, 2018).

Soil physio-chemical characteristics, such as a wide range of soil types and textures, pH (ideally between 6.5 and 7), and high organic matters maximizes nutrient availability. Also, other factors such as, 1- the quantity of available nutrition for plant to uptake from the soil and 2- the capacity of the crop to take the elements up are also considered (AHDB Nutrient Management Guide (RB209)). For instance, the capacity of the crop to take up S in 1990 with the average gross yield of 4 t/ha has been proved to be different from 2017 with 5.4 t/ha. This indicates the importance of genetic yield potential in terms of nutrient uptake efficiency (Saggo, *et al.*, 2018). It is estimated that N management systems in UK agriculture could cut GHG emissions by 2.1%, while genetic improvements could reduce this issue by 5.0% (Defra, 2010b).

2.2.4. Development of oilseed rape varietal

Various types of cultivars may be chosen for different markets, however, gross output, meaning yield adjusted for oil content, is the most important factor when a variety is selected (Nutrient management guide, 2018). Other characteristics such as lodging resistance stem shortness and stiffness, maturity and flowering earliness, disease resistance, oil and glucosinolate contents are also important. After 1970s, when OSR production became attractive as an autumn sown variety with higher yield potential than spring varieties, the major breeding effort was to reduce its glocusinolate compounds as an unfavourable metabolite for livestock. As a result, the first double- low varieties, Darmor, with lower level of glocusinolates was introduced in 1984 and enhanced commercially. However, this variety impaired the yield by 3% and it took several years to overcome (Booth, *et al*., 2005). In 1990s with developments in breeding, hybrid varieties became more available to growers, offering more potential for greater yields and vigour, but it was difficult to restore fertility in hybrid breeding programmes. In 1996, the first commonly available varieties using hybrid technology were varieties consisting of a mixture of male sterile and fertility restoring lines, called Synergy. Fully restored hybrid varieties followed the introduction of variety associations and by 1997, hybrids were the top yielding varieties for spring and winter. Although these varieties were performing well and had a significant share of the market, the newer, conventional, open pollinated varieties are competitive in terms of yield (Booth, *et al*., 2005). Varieties for specific markets such as HEAR (high erucic acid rape) and HOLL (high oleic, low linolenic), conventional open- pollinated varieties, known as 'pure lines' or 'inbred lines', seem to be the most economic and yield-reliable cultivars comparing to hybrid varieties and semi-dwarf hybrid varieties (Nutrient management guide, 2018). Current studies and recent research are focusing on more advanced breeding programs for the intention of reducing the reliance on N fertilizers for wheat and oilseed rape. High Yield, Low Optima (HYLO) varieties are not yet among UK variety testing programs, but they are defined as varieties with potential agronomic traits for which reducing N applications would maintain the yield, or maintaining N applications would increase yield (Sylvester-Bradley *et al.*, 2015).

The increasing use of biodiesel is a measure to improve C balance in OSR production, however, the response of the crop to the increasing rate of atmospheric carbon and climate change is important. A study on the yield and quality response of atmospheric CO_2 assessed OSR performance in a free-air CO_2 enrichment (FACE) system (Franzaring *et al*., 2008). In the experiment, plants were exposed to moderately elevated CO_2 level during a growing season to compare with ambient and control situations. The crop was responsive to CO_2 enrichment by increasing height, dry weight, and a speed-up stage growth change from vegetative to generative. Seed output including oil content did not increase significantly in the FACE system compared to the ambient situation, however, pod wall biomass was comparatively larger in the enriched CO_2 conditions. The result of the experiment highlighted the effect of the CO_2 fertilization on the growth indices and/or yield enhancement so as to help plant breeders select lines mainly responsive to a significant increase in seed and oil yield.

2.2.5. Pests

After or even before the emergence of the seeds, a considerable plant loss can be observed from grey field slugs (*Deroceras reticulatum*) when soil is moist and temperature ranges between 5 to 25˚C (AHDB Nutrient Management Guide (RB209)). Hence, in the Irish climate early sowing date (End Aug- 1st week of Sept) is an agronomic strategy to avoid slug damage that can impair crop establishment. Other pests such as cabbage stem flea beetles (*Psylliodes chrysocephala*), oilseed aphid (*Myzus persicae*), pollen beetles (*Meligethes* sp.), seed weevil adults (*Ceuthorhynchus assimilis*) and pod midgets (*Dasineura brassicae*) can be observed during crop growing season. Among all, cabbage stem flea beetles (*P. chrysocephala*) is an established, key pest of WOSR, particularly in the UK (Graham and Alford, 1981) and Germany (Zimmer et al., 2014). The pest imposes damage at larval stage by tunnelling into the leaf petioles and main stems causing significant damage through weakening the upper section of the roots and lower parts of the stems (Williams, 2004), leading to secondary fungal and bacterial infections. Adults also cause damage by feeding on stems, cotyledons and first true leaves resulting in shot-holing symptoms which lead to poor plant vigour or potential seedling death before emergence, when fields are heavily infested (Williams, 2010). In 2014, 2.7% of the national crop had serious crop losses due to adult damage, where 5-14% of this was related to the eastern and southern England (Wynn *et al*., 2014). Subsequently, it was confirmed that the average numbers of larvae/plant has risen up in all regions resulting in 1% of crop lost all over the country by 2015 (Wynn *et al*., 2017). Another species of flea beetles are *P. crucifera,* known as crucifer flea beetle; this group is one of the major late season insects causing significant damage based on the weather conditions, however, by increasing seeding rates and row spacing, a reduction of damage has been reported, while tillage system had no effect on their life cycle (Dosdall, *et al*., 1999).

2.2.6. Disease

The most common diseases affecting *Brassica* crops in a mild climate are:

phoma leaf spot/ stem canker (black leg) diseases from *Leptosphaeria* sp. Greyish and yellow-brown leaf lesions with small black pycnidia appearing during vegetative growth, and stem canker after flowering, corky dry rot at the base of the stems with necrotic lesions are typical symptoms. In a situation where the stems are surrounded by rot, plant tends to lodge at ground level (Davies, 1986).

Light leaf spot: Early symptoms appear as white colonies, and then the infected tissue turns brown and necrotic. Infected stems also have black speckling; severe infection can result in stunting plants over winter or can cause damage to buds, flowers and pods (Davies, 1986). Sclerotinia Stem rot, symptoms of this soil-borne pathogen can be visible as white lesions on the stems after flowering due to the absicion of infected petals. It can then be found inside the stems or pods when humidity and temperature are favourable for the disease to spread (Davies, 1986). Similar climate conditions can cause Club root (*Plasmodiophora brassicae*) to spread which is another soil-borne disease. The fungus induces gall formation on roots resulting in malfunctioning of the root system, wilt symptoms, stunting, or even water stress, and may ultimately lead to a yield reduction (Davies, 1986). Long crop rotations, better drainage, and liming to achieve a pH up to 7.2 might enhance the host resistance to this pathogen (Dobson et al., 1983). Excessive application of N fertilizers results in the increase of frost damage sensitivity during autumn and increasing foliar diseases from the dense canopy and lodging (which will be discussed in this section). Moreover, increased N fertilizer enhanced the infection of downy mildew (*Peronospora parasitica*), verticillium wilt (*Vertilicillium dahlia*), reduced N application mitigates the appearance of stem rot (*Sclerotinia sclerotiorum*), whereas the infection of blackleg (*Phoma lingam*, syn. *Leptosphaeria maculans*) was not related to the N application (Söchting and Verreet, 2004). However, in one study, a susceptible WOSR cultivar showed more crown canker development at early sowing date than a more resistant one (Aubertot, *et al*., 2004).

2.2.7. Weeds

Weeds are plants growing where they are not wanted; they cause crop production problems such as yield reduction due to competition for light, nutrients, and space. Also, their presence can be related to a loss of quality of the crop as the result of contamination with weed seeds at harvest time (Walker and Booth, 2001). The main potential weed is the volunteer OSR appears because of tight crop rotations, as these plants are particularly competitive. Also, broad-leaf weeds need to be controlled using pre-emergence approaches. This is mainly because spring herbicide options are limited for OSR. Therefore, weed control is carried out before drilling based on crop establishment methods and weed presence. Pre-drilling methods encourage weed growth and control from harvest to drilling and can reduce herbicide resistance risk. For controlling grass weeds such as black-grass (*Alopecurus myosuroides*), using propyzamide- based herbicides is suggested where deeper cultivations are used (Managing arable weeds, AHDB Nutrient Management Guide (RB209)).

Based on the International herbicide-resistant weed database (Heap, 2022), common Chickweed (*Stellaria media*), Corn poppy (*Papaver rhoeas*) and poverty Brome (*Bromus sterilis*) have been identified as resistant in Germany rapeseed fields in 2011 and 2012. *S.media* and *P.rhoeas* were resistant to the herbicides functioning on the inhibition of acetolactate synthase, such as florasulam and imazamax, and *B. sterilis* was reported as resistant to the herbicides of group Acetyl CoA carboxylase inhibitors, i.e. cycloxydim and propaquizafop.

2.2.8. *Lodging*

Adequate N fertilization increases WOSR yield through more vegetative growth, reproductive development and seed number or size increase. Inadequate N application, therefore, restricts yield production (Grant and Bailey, 1993), but excessive N application results in yield reduction (Lääniste, *et al*., 2004) by promoting lodging (Scott *et al*., 1973; Wright *et al.*, 1988). Lodging leads to nutrient and moisture movement restriction to oilseeds, and is a hindrance for crop harvest by delaying crop maturity (Scott, *et al*., 1973).

Lodging, which is defined as a stem angle of more than 45° from the vertical position, induces yield loss by 13% as a moderate amount up to 50% in a severe situation (Baylis and Wright, 1990). Lodging in oilseed rape has been proven to be as the result of either 'failure of the anchorage system (root lodging) or from buckling of the stem (stem lodging)' (Berry and Spink, 2009). Goodman *et al.* (2001) investigated the mechanism of lodging and defined the necessities of the vigour of the taproot and the strength of the surrounding soil. Generally, crops might have a greater tendency to lodge for the reasons of early sowing, a dense plant population establishment, and early application of N with an overgrown canopy (Lunn *et al*., 2003). Baylis and Wright (1990) showed that crop lodging could reduce yield by up to 50%. It is noticeable that 'the height of the plant is a key determinant for lodging control' (Berry and Spink, 2009); however, to reduce the risk of lodging and similarly yield improvement, the application of plant growth regulators, namely, anti-gibberellin triazoles, such as metaconazole, between green bud and early flowering can increase yield. Small and non-significant reduction of plant height can result in high seeds/m^2 and root system functioning enhancement (Berry and Spink, 2009).

2.2.9. *Pod shattering*

Practically, the crop is mature when all seeds turn black, and seeds` moisture content is less than 15% (Pouzet, 1995); early harvesting can reduce seed quality and late harvesting can enhance pod shattering. A bad combine harvester setting might result in seed loss up to 0.5 t/ha for non-susceptible cultivars to shattering (Szot *et al.*, 1991). However, it is possible to minimalize seed losses by the means of some adaptations of the combine-harvester. The actual physical status of the canopy can be considered to reduce the loss, there are items to note such as: sloping of the canopy, pod wall moisture content, seed moisture content, the phase of maturity, date of harvest, the susceptibility of the individual variety to pod wall cracking, seed shattering and shedding (Szot *et al.*, 1991). Owing to that, chemical desiccation is used to reduce seed loss without any harmful effect on seed quality or yield due to weathering. In some situations where desiccation cannot be used, swathing allows the crop to achieve an even maturity and can be a good practice to prevent seed loss due to winds in standing crops. Seed loss in terms of method of harvest had no significant effect on yield reduction, in either way of desiccation or swathing (Bowerman, 1984). Chemical pod sealant, namely, di-1-pi-menthene increased pod resistance to splitting, but had different effects on various cultivars (Szot and Tys, 1987). One of the effective factors for pod shattering can be attributed to lodging, as well (Armstrong and Nicol, 1991). Breeding programs for shattering resistance can be an advantage, but in some regions with strong winds, the problem might not be rectified. Bowerman (1984) discussed that cultivars with stems that can lean to form a weatherproof canopy together with high resistance to pod shattering can be the most easily compromised by wind.

2.3. Physiology of yield

2.3.1. Phenological stage

Growth means an increase in the size of an organ that leads to the accumulation of dry matter, sugars, structural and storage materials in leaves, stems, and eventually fruits. However, development is a progression of a crop along the stages of its life cycle (Mendham and Salisbury, 1995). For timing management operations: herbicides, fertilizers, pesticides etc. a definition of plants` life cycle quantified numerically is useful. An attempt has been made (SB growth stage) by Sylvester-Bradley *et al*. (1984), in which the life cycle is divided into 10 principal stages, with secondary stages for each subdivision. In addition, these principal stages are not necessarily exclusive, for example, ‘plants can be elongating stems at the same time as flower buds are developing’ (Mendham *et al*., 1981). The interaction between growth and development builds up the actual yield in the crop, and each stage and process is under genetic control and affected by environmental factors such as temperature. It is believed that the growth stage system for WOSR needs to be updated. Sylvester-Bradley *et al*. (1984) growth stage was developed when crops were sown at higher plant densities and consisted predominantly of main racemes (with not many branches). Mid-flowering is based on 50% of flowers opened on the main raceme but this description was acceptable on WOSR for over 30 years ago genetic pool (Berry, Email communication, April 02, 2020). Consequently a new version of growth stage has recently been adapted from Sylvester-Bradley (1984) system under the name of AAB (AHDB, 2020). Another system of coding namely BBCH facilitates GS descriptions with the same underlying concept as Sylvester-Bradley system but different coding numbers (Lancashire *et al.*, 1991).

Briefly, seed germination is affected by soil moisture and temperature. After seedling emergence, crops commence leaf production, floral initiation, stem elongation, bud emergence, flowering, pod formation, seed filling, oil formation, seed maturation, and plant senescence. The plant apex initiates leaf formation until it turns into a reproductive organ. The number of leaves is dependent on the vegetative stage. At the same time, secondary branches with clusters of flower bud can appear on *Brassicae* as an indeterminate crop. Therefore, depending on the environmental conditions, the crop is able to produce up to 20 to 25 secondary branches, as a compensation for poor establishment, or aborted seeds and pods (Kirkegaard *et al.*, 2021). Seed fill in *Brassicae napus* starts at maximum size of pod hulls, then seed filling progresses with the expansion of seed coat containing liquid endosperm, embryo growth, and increasing oil content (Diepenbrock and Geisler, 1979).

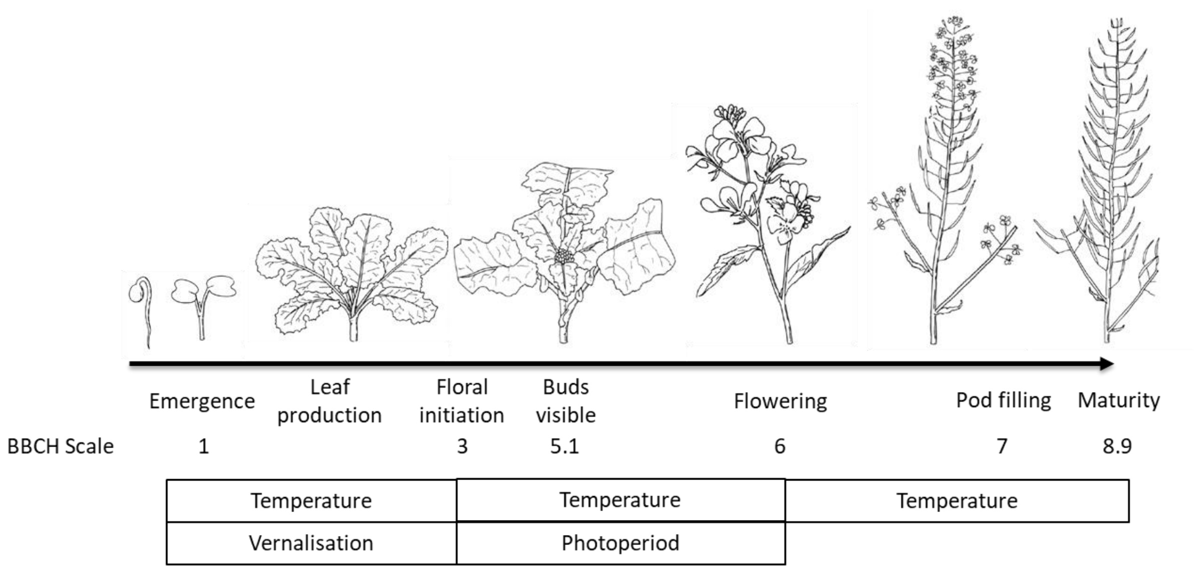


Figure 2.5. Scale of BBCH showing growth and developmental stages of *B. napus* with its environmental factors affecting developmental phases (Taken from Kirkegaard *et al*. (2021))

2.3.1.1. Temperature

For phenological development, a duration of required temperature is needed so that the plant enters the next phase. The rate of this development is a linear function between a base and an optimal temperature, beyond which the rate of development slows down. Calculations of thermal time take optimum and maximum temperature into account (Mendham and Salisbury, 1995)

2.3.1.2. Vernalization

A decrease in the thermal time duration of the vegetative period with an increased duration of cold or a set period of cold (accumulation of chilling hours) can both be triggers for a change in developmental stage. As soon as vernalization satisfied the limit, a quick developmental transition to the generative phase takes place in many varieties, under different field conditions (Ferreira *et al.*, 1995; Raman *et al.*, 2011).

2.3.1.3. Photoperiod

Brassicae genus is a long-day plant, meaning that by increasing day length (between circa 10 to 16h) (Robertson *et al.*, 2002) a reduction in thermal time is required for reaching flowering time. Therefore, for winter varieties, a period of cold temperature and an increasing day light would result in early flowering (reduction in thermal time).

2.3.2. The Potential Yield of OSR

Under maritime climate conditions (UK and Ireland), the most limiting resource is the availability of light. In order to use the available solar radiation as efficiently as possible, the acquisition of other resources such as nutrients and water need to be optimized for the crop. Therefore, the production and partitioning of dry matter to obtain the maximum possible yield requires some general optimizations in crop traits, which are the improvement of: 1.rooting depth for better nutrient and water uptake, 2. NUE, 3. pre-flowering assimilation and productions, 4. sink capacity, 5. post-flowering radiation use efficiency, 6.sustainable disease and pest control and 7. safety against seed loss and pod shattering at harvest (Spink *et al.*, 2009). All of these are associated with increasing productivity. It is believed that some improvements can be made in a short time frame (<5 years), mostly via husbandry approaches, while many others may not be obtainable for 10-15 years through breeding programs (Spink *et al.*, 2009). The potential yield of oilseed rape has been increasing by 0.05 t/ha per year with UK breeding programs, nonetheless, a greater yield potential can be associated with an optimum N fertilizer rate. Generally NUE in OSR is low, but any possible mechanism which would help the crop capture the maximum amount of radiation, with least N application, or any N acquirement that comes from mineralization or fertilizer uptake efficiency are all contributors to N use efficiency improvements and would impact on optimum N rate (Berry *et al.*, 2008). As noted earlier, improving rooting systems for better water uptake is a yield increasing strategy. However, oilseed rape has been shown to have a limited root growth system at depth (20-40 cm), which results in premature senescence during seed filling (Spink *et al.*, 2009). Therefore, any change for prolonging growth or increasing growth rate would mean a higher crop water demand. In this case, water supply and/or capture can be a limiting factor for increasing proportion of crops and/or the conversion to dry matter for any yield improvements (White *et al.*, 2015). One study on oilseed rape roots showed root depth can reach at least 1.8 m, with a root length density (RLD) of about 8 cm/cm^3 in the top 20 cm of soil (Barraclough, 1989). As RLD is an important plant trait based on water changing availability, where water is not a limiting factor, RLD is greater in the topsoil, but during drought it can increase deep in the soil profile (Blum, 2005). White *et al.* (2015) used a study model to explore the relationship between crop RLD, water uptake and yield. It was noticed that for crops where 1 m of root depth was considered, an increase in RLD would result in a yield increase, as expected. However, the effect of deeper rooting system, of up to 1.8 m, did not necessarily add to yield. It was considered that if roots reach to further depth, sufficient RLD would also be achieved, as extending the depths of poor root systems had little effect due to deep but small RLDs.

Other examples of agronomy practices which help maximize yield are suggested to be sowing one week earlier in maritime climate, so that leaf area would be increased by forwarding flowering time to cooler days. Reflection of light due to decreased flowering canopy would be reduced, and therefore, the radiation use becomes efficient for a higher photo assimilation during pod and seed filling (Mendham and Salisbury, 1995). Early sowing date in UK climate would result in flower cover being reduced by 0.25/area, increasing leaf area, then photo assimilation lengthens by 39%, meaning that the number of days required for receiving the radiation increases, hence seed number is determined in the meantime (Berry and Spink, 2006). Applying this technique to crops with optimum number of pods (between 6000 to 8000/m^2) would increase number of seeds/m^2 (Berry and Spink, 2006).

Yield of winter oilseed rape in the UK averaged 3.166 t/ha from 1980 to 2018. In Ireland, also, it has been recorded as 3.188 for the same duration (FAOStat, 2020), whereas small individual plot trials according to AHDB Nutrient Management Guide (RB209) can go as high as 6 or 7 t/ha, and there are studies in which 130,000 seeds/m^2 have been recorded but each pod contains lower number of seeds (19 seeds) (Fray *et al.*, 1996; Mendham and Salisbury, 1995).

It is considered that these limitations can be improved by tailoring agronomy practices, genetics and physiological knowledge to reach 5.7 t/ha of yield by 2050. Theoretical and realistic potential yields are around 9 t/ha and 5.19 t/ha, respectively, while noticing 5.19 t/ha is feasible under light and water limitation, while the yield was as high as ~ 4.57 t/ha (Sylvester-Bradley *et al.*, 2005). The physiology of yield formation has three main periods: the foundation, crop construction, and finally yield-forming (Sylvester-Bradley *et al.* 2002). In this literature review, yield formation is considered in reverse order; starting from yield formation period to germination and plant establishment.

Depending on the genotype, sensitivity to temperature, vernalization and photoperiod explain the difference in the duration of the phases from emergence to floral initiation, floral initiation to bud visible, bud visible to flowering and flowering to maturity. Increasing photoperiod and temperature shorten the plant growing stages, whereas some varieties develop more under the influence of cool conditions (Mendham and Salisbury, 1995; Robertson *et al.*, 2002).

2.3.3. Yield forming period

In the vegetative plant phase, leaves are the most important photosynthetic organs, however, during or after flowering, leaf areas tend to be reduced, and instead, stems and later pods take over. To maximize crop yield, the size of the photosynthetic canopy should be optimized, so that it can guarantee a sufficient aboveground biomass that meets the sink capacity (pods/m^2 and seeds/m^2). This is to avoid excessively large canopies resulting in poor radiation interception beneath the crop and lodging risks (Sylvester-Bradley *et al*., 2002).

During the flowering stage, the yield potential is set, meaning that a balance between vegetative growths and the potential number of flowers, pods, and seeds, has already set. After flowering, stem dry matter tends to be at its peak and pods are already lengthened, so seed filling is dependent on post-flowering photosynthesis assimilates (Mendham *et al.*, 1981), and pods possess 64% of the total green area by post-flowering (Scott *et al.*, 1999). The procedure from which yield is formed depends on the supply of solar radiation over the plant`s growth stages and, the proportion of the incident radiation that is intercepted by the canopy. The efficiency of the intercepted solar energy itself depends on the carbon-fixation process, which leads to form the plant dry matter, distributing among the organs of the crop, foremost within the harvested organs (Hay and Porter, 2006).

The yield of oilseed rape is composed of two main characteristics: the number of seeds/m^2 and the individual seed weight. The former component is a more important index for yield determination. The current yield is believed to be sink limited, meaning that the number of generative organs, such as seeds per m^2 are restricted (Berry and Spink, 2006; Sylvester-Bradley et al., 2002). However, yield can be limited by source (vegetative organs) (Clarke *et al*., 2017), hence, a balance is needed between leaves that generate assimilates (as source) and the harvested organs that store these compounds (as sink). Source and sink are not independent; sinks are constructed from the built-up assimilates from source, so that, 'sink capacity is determined by the availability of assimilate' (Evans, 1996). The ability to capture and utilize radiation during flowering and after that, can affect yield formation extensively (Booth *et al.*, 2005). The number of seeds/m^2 can be determined during the phase for pod and seed abortion about 300 ° Cd (degree-days) after flowering. Pod and seed survival are related to the intercepted radiation by photosynthetic organs, respectively per flower and per pod after flowering (Mendham *et al*., 1981). But the flower layer can be a deleterious factor as it may reflect or absorb 58% of the photosynthetically active radiadiation (PAR), with flower coverage of 0.62 of the area at flowering (Yates and Steven, 1987). Berry and Spink (2006) showed that seed number/m^2, pod number/m^2 and seed number/pod are all negatively related. Hence, an optimum fertile pod number is between 6000 to 8000 /m^2; fewer than 6000/m^2 pods are considered as small canopies that are not able to absorb enough of incident radiation; alternatively over 8000 pods/m^2 means dense flower layers which restrict radiation reaching potential photosynthetic tissues. In both cases, seeds/m^2 and seeds/pod gradually reduced. If seed number could be increased to 150,000/m^2, then there would be enough capacity for the crop to become source limited (Berry and Spink, 2006).

Conclusively, in the UK climate, the biophysical potential yield is composed of the vegetative biomass and the amount of dry matter that is accumulated during seed filling, which are dependent on available light and water resources (Berry and Spink, 2006). It is obvious that more vegetation can result in a higher number of pods/m^2; however, radiation transmission to the canopy and younger pods (on lower parts of the plant and the lowest pods on the terminal raceme) will be reduced due to reflection and absorption by the upper layers of flowers (Fray *et al*., 1996).

Seed yield is the most complex trait in OSR compared to other crops, and the complexity is related to the crop growth potential and branching after flowering, enabling the crop to use one yield component to compensate for the limitation of another one. Hence, yield components consist of factors such as: plants/m^2, pods/plant, seed weight and seed quality etc. (Diepenbrock, 2000). As described, all the components are dependent on the developmental traits, such as flowering time, seed filling duration and also environmental conditions, namely climate, water and fertilizer availability (Bouchet, *et al*., 2014).In an earlier study by Allen and Morgan, (1972) N application increased yields of seed and oil through increased production of seeds by a larger number of pods. However, the application of N had little effect on average pod weight or average seed weight, directly. It is the growth rate that mainly is defined by pod development through leaf area maximum growth after the application of N. Effect of N, therefore, was achieved indirectly through an increase in the supply of assimilates to the flowers and young pods. Hence, the maintenance of large and photosynthetically efficient leaf area during flowering period is important for high yields in the crops

2.3.3.1. Critical stage

There seems to be a growth stage in oilseed rape, like many other annual crops, at which either yellow flowers or young pods are able to absorb 70 to 80% of incident photosynthecally active radiation in the top 60 cm of the crop (Norton *et al.*, 1991). In the stage of ‘radiation block-out’- due to yellow flowering light reflection- young heterotrophic pods and pod walls are growing speedily contributing to yield and seed number determination, simultaneously, assimilation from leaves is decreasing, therefore the abortion of some young pods/seeds is probable (Mendham and Salisbury, 1995). Mendham *et al*. (1981) found a direct relationship between the intercepted radiation from each pod layer and the number of seeds per pod at this critical stage. Flower coverage seemed to have an optimum range between 0.35 to 0.5 of area according to Yates and Steven (1987) below which there would be insufficient pod formation. To optimize the radiation penetration to the lower pod layers so as to ensure seed survival, sparser canopies were suggested by Spink *et al.* (2002), which can yield 'as well or better than denser canopies under the same conditions of incident radiation'. Agronomy practices such as avoiding very early sowings, using lower seed rates, and applying plant growth regulators can be effective in reducing flower cover (Lunn *et al.*, 2003). Another solution is the use of 'apetalous' breeding lines with 70-75% of more radiation passing through the leaf canopy resulting in 8 to 48% higher seed yields in Australia (Rao *et al*., 1991). Hence, by reducing light reflection either by using apetalous lines or agronomical practices, green parts can be more efficient in terms of capturing the potential percentage of light interception.

2.3.4. Crop Construction period

The floral structures form the yield organs. Firstly, flowers develop, fertility occurs, then seeds are set and pods form afterwards. Simultaneously, a rapid canopy growth with leaf expansion, stem extension, and branching occur. Rapid growth starts as temperature rises, and the first flowers appear in April, pod- formation is usually completed by mid-June in maritime climates (Spink *et al*., 2002).

It is common to indicate the intercepted solar radiation by the leaf area index, which is a single surface of leaf lamina per unit of soil surface area (LAI). Green area index also is a ratio of one-side of green vegetation areas of the crop (leaf, stem, and pod) to the area of the ground, which the plant is growing on with no unit. Optimum canopy size at flowering is known to be between 3 and 4 units of GAI (Berry and Spink, 2006). Mendham *et al*. (1981) reported, before full flowering (full flowering in this study refers to 7 days after half the plants have their first flowers open); the highest leaf area was obtained at less than 4 units of GAI. This is believed to be enough to intercept 90% of solar radiation. After flowering stage, leaves will be shaded by the large yellow flowering canopy and by pods at a later stage. Dry weight of the crop declines temporarily as leaves drop down, but soon developing pods appear as significant photosynthetic area. Physiological studies by Mendham *et al.* (1981) suggest that crop weight by full flowering may be an indication of the 'photosynthetic capacity, potential pod number and/or seed-bearing capacity of the crop.'

The effect of N on GAI expansion is known and has been integrated into OSR simulation models (DAISY model: Petersen *et al*., 1995; CERES model: Gabrielle *et al*., 1998b). Contained within the models is information on water dynamics, soil temperature, N dynamics including sub-models for soil organic matter turnover, N transformations and movement of N etc. and the relationship should be sought between N effect and radiation use efficiency (RUE). Andersen, *et al*., (1996), however, did not find any relationship between N fertilization and RUE on WOSR.

Lamiare and Gastal (1997) suggested that the N status of a crop may be assessed by using the N nutrition index (NNI), later on, CERES-Rape model was able to quantify the N status on GAI and obtained significant over-estimation of DM for unfertilized crops. The authors hypothesized that RUE decreased in response of N deficiency in crop simulation models, and therefore the importance of N effect on RUE needs to be studied as a function which depends on the GAI (Justes, *et al*., 2000). This will be discussed in chapter 4 of this thesis, which describes the stepwise relationship of the effect of N on canopy formation (GAI), radiation interception, dry matter and yield.

2.3.5. Leaf initiation, growth and development, germination and establishment (The foundation period)

Soil temperature is the main factor helping seeds germinate once imbibition occurs. In areas where autumnal temperature is not restricting (is a constant temperature), soil moisture can be as important as temperature (Mendham *et al.*, 1981).

This stage is composed of plant establishment, leaf and branch appearance, and stem extension during autumn. However, the growth condition depends on the correct timing of sowing and weather conditions (Mendham *et al*., 1981). During winter, leaf senescence occurs, and because growth usually stops, new and limited leaf expansion may not be a compensation for bigger leaf area loss. Initiation of flower buds is controlled by vernalization and photoperiod, for which plants are responsive between November and February in maritime climates (Mendham *et al*., 1981). The number of leaves initiated before floral induction can influence the number of pods on the branches developing from initials in the leaf axils. A general pattern of growth is described by Mendham *et al*. (1981) for oilseed rape in European climate conditions; considering the sowing date, a rapid growth is expected after crop establishment in autumn, then growth rate will be slowed down or even dormancy can happen during winter. At this stage, leaf area index may decline, because early grown larger leaves are now replaced by small young leaves that are still developing under low temperature. Rosette stage is mostly significant until before rapid stem extension starting in spring. In early sown crops or high populated and dense plants with larger leaf areas, first internodes appear in autumn (Leterme, 1988). Therefore, depending on the sowing dates, inflorescence initiation may occur in November, or can be delayed for late- sown plants until early spring. Roughly, half way through the spring growth period, yellow flowers begin to appear.

2.4. Nitrogen Requirement

The available form of N to be taken up by the crop is ammonium or nitrate ions essential to produce amino acid chains or form nucleic acids (Wild, 1988). The OSR crop takes up a considerable amount of N by flowering, and then it redistributes all assimilates to pods and seeds from leaves and stems (Mendham *et al*., 1981). Moreover, pod walls can also act as an N reservoir to supply 25% of this element to the seeds (Hocking and Mason, 1993). Nitrogen at the rosette stage to early stem extension has the most yield benefit, compared to other growth stages (Bernardi and Banks, 1993).

According to this principle, when N is low, application of N increases both crop growth and N concentration in the plant up to a critical value where crop growth is at the peak. After this, applying more N only increases tissue N concentration. This stage of growth corresponds to the final yield determination that is believed to include 90% to 95% of the maximum yield (Fig 2.6.). If N application is less than optimum, leaf senescence and limited PAR absorbance occurs, at a period when leaves could still be functioning for intercepting radiation and yield formation (Behrens *et al*., 2011). Therefore, N fertilizer requirement is associated with proper timing and rate. In other words, the N requirement or economically optimum N rate is the rate at which a further increase of N application will result in higher fertilizer costs than any valuable additional yield production. It is also important to consider a ratio of the prices of yield to the value of N in fertilizers; the ratio is defined as breakeven ratio (BER): amount of crop yield (kg) required paying for one kg of N fertilizer (Nutrient Management Guide, (RB209)). Ideally, predicting the optimum N rate is appropriate when a comparison of NUE at its economical optimum N rate and an N response curve alongside the yield is defined, so that a better understanding of practical and economic differences is obtained (Storer *et al.,* 2018).

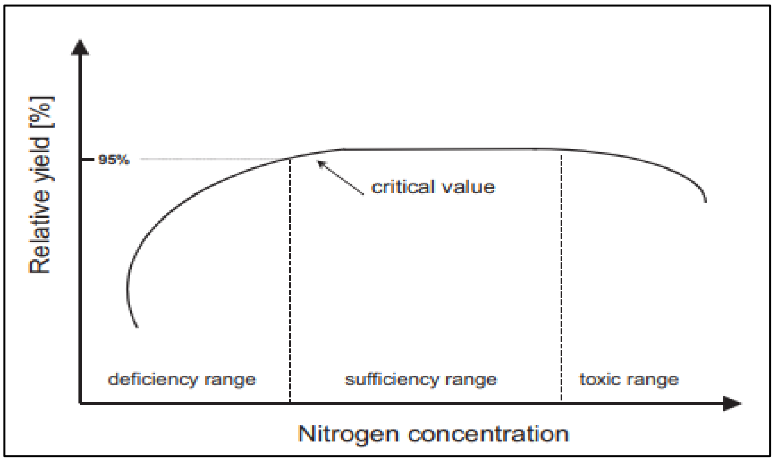


Figure 2.6. The importance of N concentration in relation to a relative yield value (Taken from Olfs *et al.* (2005))

Nevertheless, in terms of crop N requirement and fertilizer rate for OSR, decision making is not as easy as for cereals due to the fact that the relationship between N utilization and seed yield is not clear (Pouzet, 1995). For instance, one tonne of harvested WOSR with 42% oil and 38% protein in the meal contains 35 kg of N, but 70 kg is the amount that is accumulated by the plant for 1 tonne of seed production. Hence, for high yield it needs a substantial amount of fertilizer N, 150 to 200 kgN/ha to produce 3 tonnes of seed per ha. On the contrary, winter wheat as an example, in continental climates needs 30 kg N uptake for each tonne of seed production, considering that each tonne removes 22 kg N (with 13.75% protein), an application of 210 kg N/ha produces 7 t/ha of yield. In addition to fertilizers, soil mineralization also contributes to the decision on N application and N requirement, and is calculated on the basis that 70 kg should be used for every tonne of seed production according to Pouzet (1995). Notably, the amounts of N fertilizer above 200 kg/ha resulted in dramatic increase of N leaching. Hence, precise calculation of N fertilizer rates must consider the SMN that is available to the plant to uptake, and crop N demand (Appel, 1994).

For considering soil mineralization calculations, two factors are important: firstly, the amount of mineralized N at early spring (Soper, 1971), which is usually low - particularly in continental climates - because N absorption had been high in the previous autumn (Pouzet, 1985; Reau *et al*., 1994). Secondly, the N that will be mineralized during spring depends on climate conditions, which are usually tested with experimental yield and N responses. French experiments revealed that the total N from mineralization of soil and crop residues is usually between 50- 80 kg/ha, in some situations, the crop yields up to 3.5 t/ha without applying any N fertilizer (Bilsborrow *et al*., 1993).

A general approach from French studies according to Reau *et al.* (1994) assumes an equation as per below, where Y is the expected yield (t/ha) and a need of 70 kg of N for each tonne of seed production are predicted (Pouzet, 1995). Therefore, the amount of required N fertilizer (shown as X in equation 1) is predictable when mineral N in the soil after harvest (N_h), during autumn (N_a) and spring (N_s) are taken into account, according to the equation (Eq.2.1) below:

Required N fertilizer: $70 \times Y = X - (N_h + N_a + N_s)$ (Eq.2.1.)

2.4.1. Nitrogen Use Efficiency (NUE) in winter oilseed rape

A basic definition of NUE was suggested by Moll *et al.* (1982): NUE is seed yield that is produced per kg of available N (Eq.2.2). Total NUE is divided into two main components: 1) N uptake efficiency (NUpE) - this describes the ability of the crop to take up N from soil or fertilizer (Eq.2.3), and 2) N utilization efficiency (NUtE) - the ability to utilize the absorbed N to produce seeds (Eq.2.4).

$$\text{N use efficiency } \left(\frac{\text{kg}}{\text{kg}}\right) = \frac{\text{seed yield}}{\text{N supply}} \qquad \text{(Eq.2.2)}$$

$$\text{N uptake efficiency } \left(\frac{\text{Kg}}{\text{Kg}}\right) = \frac{\text{Total N uptake}}{\text{N supply}} \qquad \text{(Eq.2.3)}$$

$$\text{N utilization efficiency } \left(\frac{\text{Kg}}{\text{Kg}}\right) = \frac{\text{seed yield}}{\text{total N uptake}} \qquad \text{(Eq.2.4)}$$

Fertilizer N recovery with an agronomy concept is defined as below (Craswell and Godwin, 1984):

$$\text{Agronomic N efficiency}\left(\frac{\text{Kg}}{\text{Kg}}\right) = \frac{\text{seed yield (fertilized)} - \text{seed yield (unfertilized)}}{\text{Fertilizer N supply}} \quad \text{(Eq.2.5)}$$

In terms of physiological N use efficiency, seed yield and N uptake are defined as below:

$$\text{Physiologic N efficiency}\left(\frac{\text{Kg}}{\text{Kg}}\right) = \frac{\text{seed yield (fertilized)} - \text{seed yield (unfertilized)}}{\text{N uptake (fertilized)} - \text{Nuptake (unfertilized)}} \quad \text{(Eq. 2.6)}$$

Physiologically, NUE explains a C:N balance in the shoots at harvest showing the relationship between biomass and the N content of the shoots and whereas the agronomical N efficiency describes a direct increase in the seed yield for each additional unit of N fertilizer, and the capability of the plant to convert N to seed yield. The difference of the obtained seed yield between two different N regimes is shown by ratios (Eq.2.6) (Good *et al.*, 2004; Rathke *et al.*, 2006).

2.4.2. The importance of improving NUE

There are two ways by which NUE can be improved: 1- by reducing the N requirement while maintaining yield, and 2- by increasing yield without increasing N requirement. To achieve either of these routes, the available N needs to be taken up by the crop efficiently, for example, through improved rooting system. Poor rooting at depth with N uptake slowing down dramatically after flowering, are reasons for low NUE. The remobilization of N from canopy to the harvested seeds is weak, in such a way that only 50% of the N content in the canopy is harvested from the seeds (Sylvester-Bradley et al., 2015). Improving NUE is achievable through agronomic and genetic improvements; agronomic practices affects NUE by affecting yield (Sylvester-Bradley et al., 2015). Higher NUE can result in reduced N use with consequent environmental and economic benefits. However, greater value of NUE can be achieved at zero N rates, with the lowest yield, so growing crops at zero N means more demand for cropped areas which brings no benefits to farmers (Storer *et al.*, 2018). In conclusion, NUE is not an adequate target for the arable industry, while a better target is to reduce N application when maintaining the yield or improving yield by maintaining N application are suggested.

The crop NUE value is best expressed at the optimum N level, based on the curves fitted to the yield data from multiple N fertilizer rates. Yield should be mentioned at its optimum N level, because if a variety has a low yield and a low N optimum N rate, then the NUE is still high. Therefore, it is vital to compare NUE at its economical optimum N rate on an N response curve alongside yield so as to have a better understanding of practical and economic differences. As described earlier, zero N crops might be able to reach as high NUE value as N applied crops, but the optimum yield is not satisfactory (Fig 2.7) (Storer *et al.*, 2018; Sylvester-Bradley *et al.*, 2015). Similarly, above ground crop N uptake and N utilization efficiency have mostly been used to determine N requirements, and in the case of oilseed rape, many studies showed that at low N supply level, seed yield is more correlated with N uptake than N utilization efficiency (Berry *et al.*, 2010b; Nyikako *et al.*, 2014; Schulte auf'm Erley *et al.*, 2011). However, it has been suggested that N utilization would be strategically improved by increasing sink capacity (seeds/m^2), which would also improve N uptake efficiency (Berry *et al.*, 2010a; Berry *et al.*, 2010b). While improving N remobilization from stems to seeds after flowering relies on NUE genetic enhancement, it also results in greater N remobilization (Bouchet *et al.*, 2016; Girondé *et al.*, 2015).

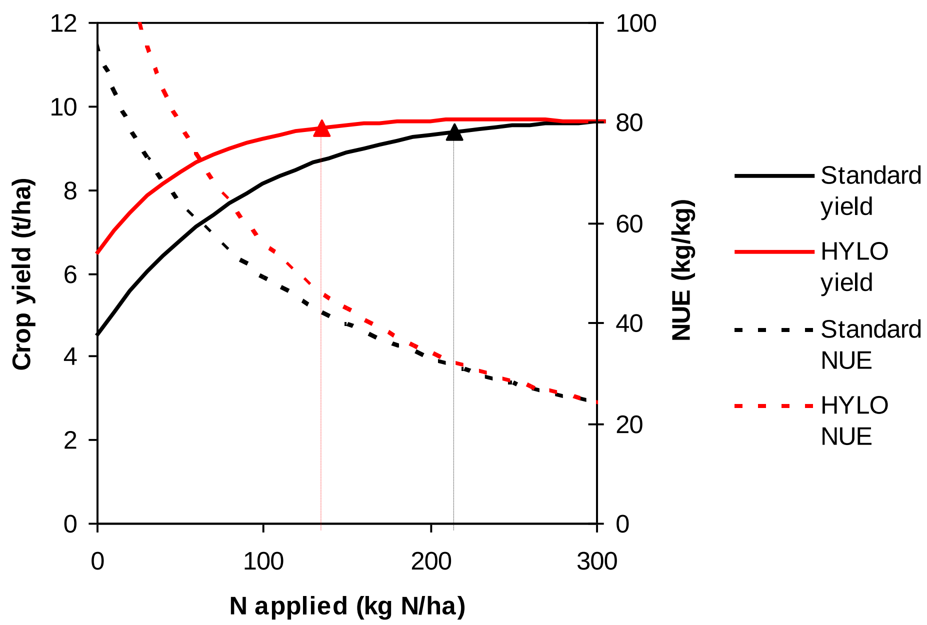


Figure 2.7.The effect of applied N on crop yield and NUE for a standard wheat variety and hypothetical High Yield Low Optima (HYLO) variety with the same yield potential. Triangles are economical optimum N rates (N: grain price ratio of 5) (Taken from Sylvester-Bradley et al., 2015).

2.4.3. The concept of critical N dilution curve

Critical N dilution curves are used to determine N requirement by calculating the N content of the plants using nitrogen nutrition index (NNI), or as a model indicating the effect of N on growth and yield. A critical N curve for WOSR was built and validated by Colnenne, *et al.* (1998) under N-limiting and non-N-limiting conditions in France. Figure 2.8 shows that WOSR in comparison with wheat has a lower critical N curve for shoot biomass of 2.5 t/ha. This is related to the lower leaf: stem ratio and less N-rich tissues of WOSR. Interestingly, for shoot biomass of over 2.5 t/ha, WOSR exceeds the wheat curve, mainly due to the loss of leaves, or redistribution of N from older leaves to younger ones (Colnenne, *et al*., 1998). Also, shoot dry matter of up to one t/ha has a constant value of total N concentration in both crops. Improvements have been made in terms of factors affecting leaf: stem ratio such as the leaf area duration and phenology of the N dilution curve of wheat crops (Wang *et al.*, 2017; Zhao *et al.*, 2014). However, for WOSR, such improvements are yet to be known (Kirkegaard et al., 2020).

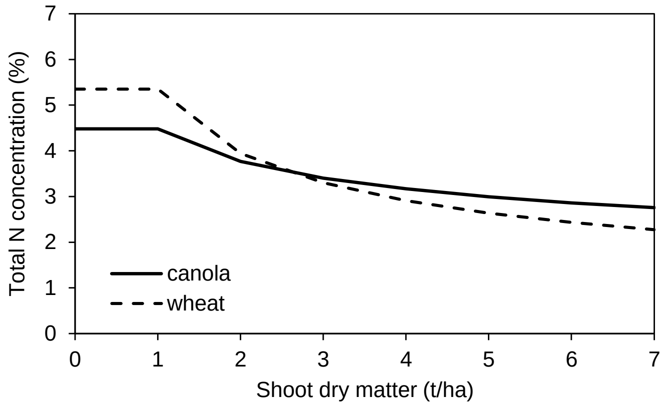


Figure 2.8. N dilution curves for winter oilseed rape (canola) and wheat during vegetation growth (Re-drawn by Kirkegaard *et al*., 2020; taken from Colnenne *et al*., 1998)

Measuring N concentration and the calculation of NNI are for scientific purposes to check the relationships between tissue N concentration and plant dry matter, and are used to study NUE in major crops, meaning that it is not a cost or time effective method to estimate N fertilizer requirement for farm purposes (Olfs *et al.*, 2005). However, a recent study showed an estimation scale of NNI of winter oilseed rape at a local scale using unnamed aerial vehicle multispectral images (Liu *et al.*, 2018).

2.5. The impact of climate types on WOSR growth, development, and N requirement

2.5.1. Climate types

Optimizing N application is a climate specific study, moreover, WOSR is a crop of temperate climates for which temperature is the major factor determining germination, vernalization, biomass production, average growth rate, and growth duration (Habekotte, 1997; Mendham *et al.*, 1981). Total dry matter of the crop is closely associated with photosynthetic active radiation (PAR) absorbance, and canopy production is proportional to the intercepted solar radiation (Monteith, 1977). Nitrogen uptake and PAR absorbance during generative phase predominantly affect yield formation. It is necessary to study N management aligned with climate conditions in countries where OSR is mostly grown. The N management principles will be described in the following sections with focus on European continental and continental/maritime countries and Ireland as the Atlantic mild climate region, separately. For more precision in terms of climate classification in the regions where WOSR is grown, Peel *et al*., (2007) was used as a guide to name regions based on the long-term temperature and precipitation associated with Köppen-Geiger climate map. The world map climate was classified based on 30 possible climate types, divided into 3 tropical, 4 arid, 9 temperate, 12 cold, and 2 polar with a consideration to temperature, shown as letters, where mutual climate characteristics will include a combination of letters. Europe consists of four dominant climate types by land area, e.g. cold (D), followed by arid (B) category, temperate (C) and polar (E), and each comprises to six levels of sub-groups (except polar category) according to the long term precipitation and temperature thresholds. Based on the Köppen-Geiger climate map of Europe (Peel *et al.*, (2007), Ireland and the UK are classified as temperate (C), both with no dry season (e.g. oceanic as category f). Whereas, the east- side of the UK (north and south) where WOSR is grown can be sub-grouped as “a” (hot summers ≥ 22˚ C), while Ireland is “b” where at least ten months in a year had a temperature of > 4˚C. Hence, Cfa for England, and Cfb for Ireland can be implied from the composite Köppen classification (Figure 2.9).

1st	2nd	3rd	Description	Criteria*
A			Tropical	$T_{cold} \geq 18$
	f		- Rainforest	$P_{dry} \geq 60$
	m		- Monsoon	Not (Af) & $P_{dry} \geq 100 - MAP/25$
	w		- Savannah	Not (Af) & $P_{dry} < 100 - MAP/25$
B			Arid	$MAP < 10 \times P_{threshold}$
	W		- Desert	$MAP < 5 \times P_{threshold}$
	S		- Steppe	$MAP \geq 5 \times P_{threshold}$
		h	- Hot	$MAT \geq 18$
		k	- Cold	$MAT < 18$
C			Temperate	$T_{hot} > 10$ & $0 < T_{cold} < 18$
	s		- Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry Winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Cs) or (Cw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a or b) & $1 \leq T_{mon10} < 4$
D			Cold	$T_{hot} > 10$ & $T_{cold} \leq 0$
	s		- Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry Winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Ds) or (Dw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a, b or d)
		d	- Very Cold Winter	Not (a or b) & $T_{cold} < -38$
E			Polar	$T_{hot} < 10$
	T		- Tundra	$T_{hot} > 0$
	F		- Frost	$T_{hot} \leq 0$

Figure 2.9. Köppen climate symbols and definitions criteria (Taken from Peel et al., (2007)).

*MAP = mean annual precipitation, MAT = mean annual temperature, Thot = temperature of the hottest month. T_{cold} = temperature of the coldest month. T_{mon10} = number of months where the temperature is above 10. P_{dry} = precipitation of the driest month. P_{sdry} = precipitation of the driest month in summer. P_{wdry} = precipitation. of the driest month in winter. P_{swet} = precipitation of the wettest month in summer. P_{wwet} = precipitation of the wettest month in winter. $P_{threshold}$ = varies according to the following rules (if 70% of MAP occurs in winter then $P_{threshold}$ = 2 x MAT, if 70% of MAP occurs in summer then $P_{threshold}$ = 2 x MAT + 28, otherwise $P_{threshold}$ = 2 x MAT + 14). Summer (winter) is defined as the warmer (cooler) six-month period of ONDJFM and AMJJAS.

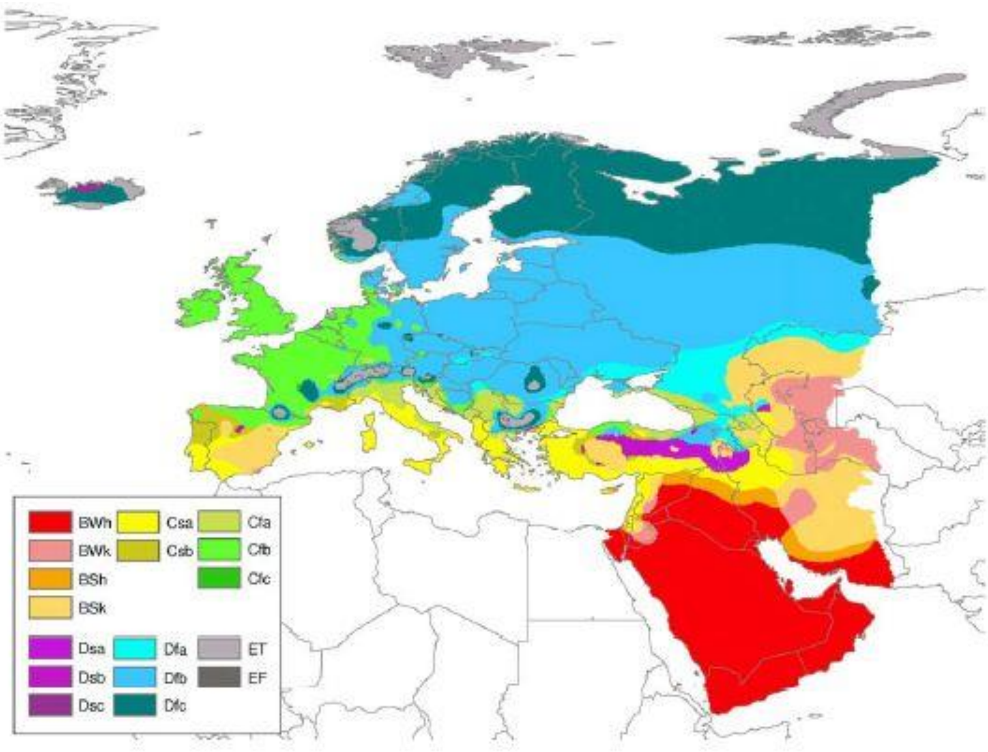


Figure 2.10. Köppen-Geiger climate type map of Europe- middle-east (Taken from Peel *et al*., (2007)).

Also, in France and Germany where WOSR is widely grown, more climate variations can be noticed, where the main categories are Dfa, Dfb and Dfc in Germany, and similarly France shows variation, with mainly Cfb class but also including all D sub-classes towards the south of the country.

2.5.1.1. climates characteristics with a focus on C and D

France and Germany have the highest concentration of WOSR in areas such as the Paris Basin (PB) (infoclimat.fr/climate) with Cfb climate category for temperate/oceanic and North (-east) of Germany (dwd.de). With east of UK, where most WOSR is grown, as climate (C) are shown to be under various influences from different air masses (Figure 2.11). Ireland is considered to have a mainly moist, mild climate with unstable airflows and frequent rain showers (Figure 2.11).

For more clarification of comparison among the named countries, thirty years of monthly average weather difference from the four European countries were gathered. Figure 2.11. represents the two categories of climate with their characteristics based on temperature, rainfall, and sunshine hours.

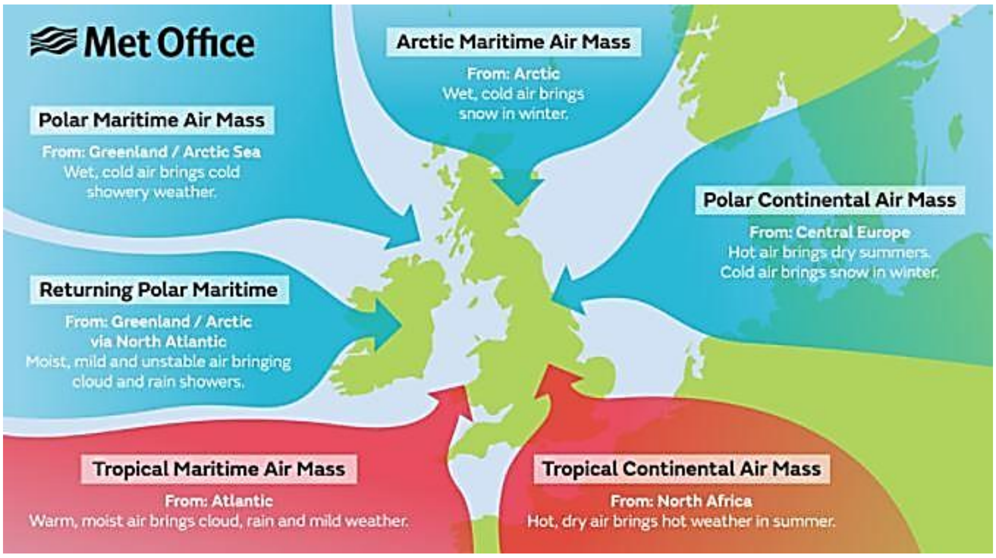


Figure 2.11. The map of different air masses on Britain and Ireland (Taken from UK Met Office)

Temperature: Central parts of France have the highest mean temperatures of the countries reduced from 19 to 12˚C in Aug, Sept, Oct, then in wintertime, temperature is stable at about 4˚C. Germany is next to France in terms of summer temperatures, the area of study in Germany is near North/ Baltic seas, yet coldest winter was measured. At the same time that this area is under the influence of high seasonal precipitation-roughly as high as Ireland- higher temperature is also observed. Therefore, humidity (moist +warmth) is implied from the graphs in north of Germany, whereas winters are the coldest.

Changing seasons from winter to spring and from summer to autumn is gradual. The average temperature in Ireland remains at a range between 5˚C during winters and 15˚C in July. East side of UK is slightly warmer than Ireland across spring and summer, whereas Irish winters are warmer.

Precipitation: Notably, in Ireland precipitation is the highest among the countries, although it is similar to north side of Germany mainly in autumn and winter as mentioned. Other regions still differ in terms of less autumnal precipitation and colder winters due to polar/continental air mass flows. Also, Ireland is shown to have higher precipitation than the East of UK, as this region seems to have an in-between (continental- maritime) situation (Mayes and Wheeler, 2013). Due to its geographical position and being close to the pathway of Atlantic low pressure systems, Ireland`s humidity and cloud coverage is noticeable for much of the time (Met Eireann, Climate of Ireland).

Sunshine hours: France, Paris Basin (PB) has on average the longest annual sunshine hours, except similar values during winter and early spring. Also, there seems to be a considerable difference between Ireland and the other three countries in terms of sunshine hours even during warm months May, June and July.

Despite the fact that there is no extreme temperature change in **Ireland**, due to the geographical position close to the pathway of Atlantic low-pressure systems, humidity and cloud airflows are noticeable for much of the time (Met Eireann). It is therefore important to note the photoperiod requirement of *Brassicae* variety in Ireland if it differs at various sowing dates. In **the UK**, generally, south and east of England are mostly under the effect of a continental condition (Mayes and Wheeler, 2013). These air masses bring temperature, humidity, and stability to the land according to the source area. For example, polar continental air masses which originates from central northern, Eastern Europe, or southern Russia meets both north and south east coast counties, where they can induce very cold snow showers in winter, specifically in south east, and forming cloud coverage in spring and summer. In **France**, the area under WOSR cultivation is distributed all around the country with specific emphasis on the Paris Basin, where most of the >100,000 ha of cultivation exists. Winter temperature fluctuates between 0 to 6˚C, 12 to 14˚C in spring, and 24 to 26 ˚C in summer, while in autumn stays at 12 ˚C again.

The average figure of precipitation showed a value of 400 mm in the altered oceanic climate areas during autumn where oilseed rape is produced. The average hours with sunshine increases from 1500 h in the north to 2800 h in autumn. **Germany**`s sunniest regions are the northern and southern edges with 1869 h of sunshine based on long term data. The average annual rainfall is 789 mm to 819 mm; summer months are considered as the wettest months with short and heavy showers sometimes with thunderstorms. According to meteorological data, in a 30- year time frame, the 'beginning of full flowering of winter oilseed rape' in spring is reported based on the accumulated thermal time; therefore, maximum and minimum days of the year that it takes the crop to reach this specific growth stage in different regions of Germany is reported. It takes a maximum of about 130 total days of the year for full flowering happen in northern parts of Germany for its humid climate, whereas on more Alpine regions with heavy rains and Atlantic low pressure of west, fewer number of days is required for full flowering (dwd.de).

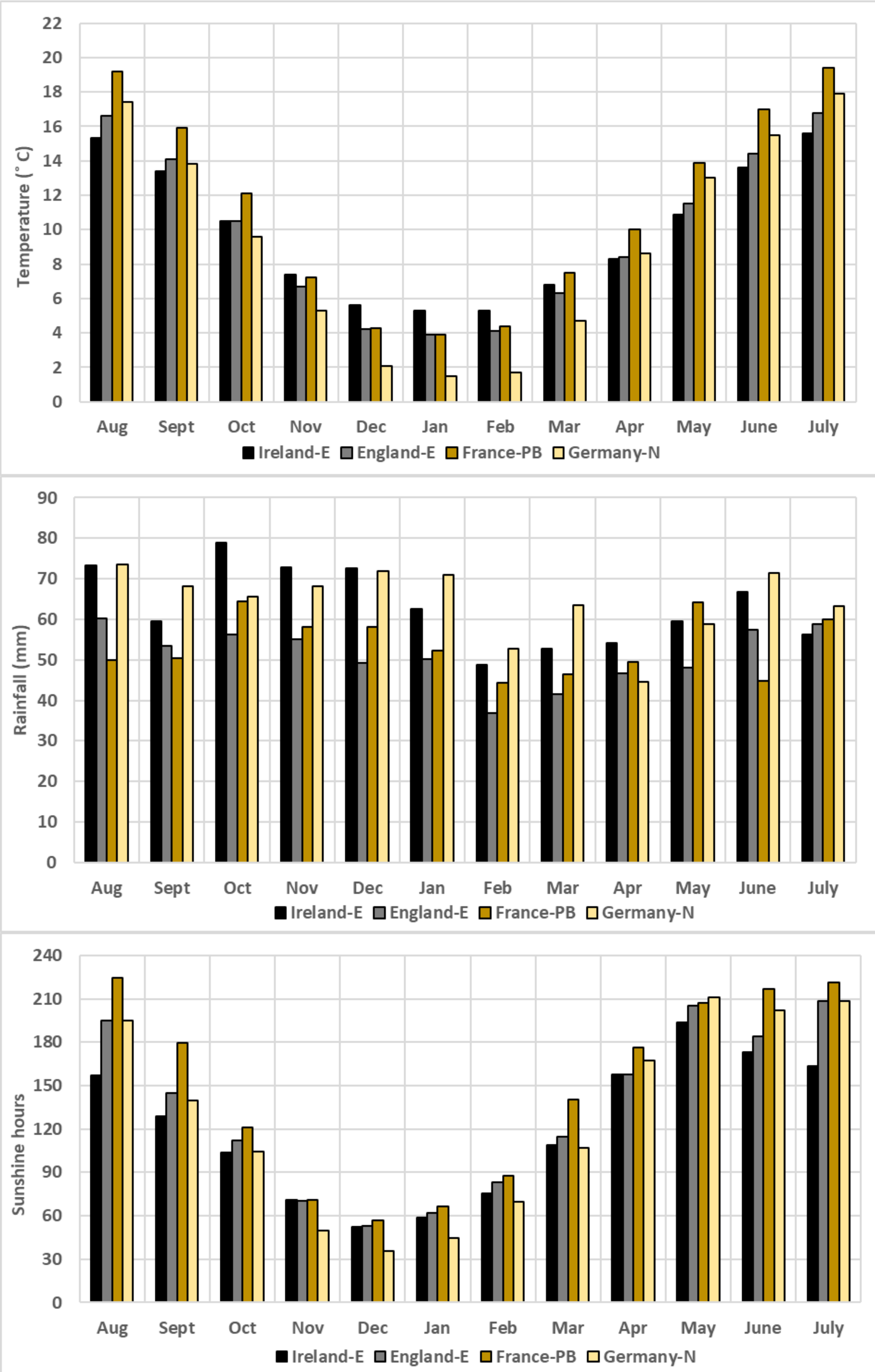


Figure 2.12. Long term monthly average Temperature, Rainfall and sunshine hours in Ireland (East), England (East), France (Paris Basin), Germany (North) from 1981-2010

2.5.2. *The effect of categories “C” and “D” climate on growth, development, and N requirement*

In continental climates where winter temperatures decrease to the frost point, WOSR requires at least 6 to 8 leaves, a tap root length of 20 cm and 1 g dry matter per plant for winter survival (Cramer, 1990). A study by Sieling *et al.* (2017) showed that the best sowing date is from the third week of August until first week of September in humid conditions of Northern Germany. This is because poor plant establishment after mid-September significantly reduced seed yield. However, if weather conditions in the following spring are favourable even for the late (after mid-September) sown crops, with two to four leaves by the end of autumn growth, the plant would still be able to reach a 5 t/ha yield (Sieling, 2017 Unpublished work). Nevertheless, since long-term weather forecasting is not yet possible, mid-September is counted as a risky sowing date with probable yield penalties. Villar *et al.* (2019) considered that early sowing dates around August lead to higher autumnal N uptake, because it is correspondent to an ideal interaction between soil moisture and temperature, which affects microbial biomass. More post winter biomass accumulation is assumed from early sowing dates, in this case, N uptake would be reduced from soil N from the stage of flowering and onwards; this is due to the fact that remobilization of N from vegetative parts to reproductive organs begins earlier when solar radiation would begin to have impact on yield formation (Rossato *et al.*, 2001). Remobilization is not a complete process as some of the N remains in the leaves, and they may fall on the soil before harvest, which can be counted as another susceptible source for mineralization (Villar *et al.*, 2019). High volumes of precipitation after harvest which coincide with warm continental summers would induce mineralization again, hence there would be an accumulation of mineralized N pool which would be available to a (catch) crop for N uptake (Cameron *et al.*, 2013). Crop N uptake depends on the temperature in autumn and winter when it comes to growth and development (Hebinger and Pinochet, 2013). N uptake accumulation before winter for an optimum development is up to 80 kgN/ha from mineralization in Germany

(Cramer, 1993). That should be deducted from the total spring N application value. During winter there is foliage loss resulting in a decline in crop N concentration of up to 80 kgN/ha maximum loss. Growth starts again when temperature consistently exceeds 5˚C, then from spring onwards, leaf canopy emerges rapidly until flowering and leaves are the main source of photosynthesis.

France and Germany take the amount of crop N at the end of autumn growth and /or early spring into account for N application (Henke *et al.*, 2009; Makowski *et al.*, 2005; Reau *et al.*, 1994). However, due to winter frost happening at these regions, leaf loss, and consequently N loss over winter results in various canopy N growth at early spring. Leaf loss in winter also has been reported in France (Dejoux *et al.*, 1999; Gabrielle *et al.*, 1998), and the recovery of N in spring was about 0.4 kg/ha near the PB. Quick leaf decomposition and subsequent N availability for WOSR N uptake in spring was concluded by Dejoux *et al.* (2000) in this region. As the result of N recovery in spring (excluding gaseous N loss), canopy N content in autumn has been estimated to be a good indicator for adjusting N fertilizer rates (Henke *et al.*, 2009) to predict N requirement. Flower bud initiation for August sowings proceeds from early November to mid-December for September sowing. Colder winters, drier summers and lower levels of precipitation can lead to a different approach for N management by mostly relying on the plant`s growth stage in these areas. An example for monitoring growth stages in Alpine and maritime regions in Germany is through meteorological data (DWD.de) in which the 'beginning of flowering of winter oilseed rape' in spring is reported based on the accumulated thermal time (Growing Degree Days, GDD) (Maier *et al.*, 2003; Müller-Westermeier, 1995).

In France, total N from mineralization of crop and soil residuals is about 50-80 kgN/ha, and in some situations a yield of up to 3.85 t/ha can be achieved under no fertilizer use (Bilsborrow *et al.*, 1993). In autumn or winter if temperatures reduce to below 5˚ C, net mineralization will be reduced to <1 mgN/kg/day even under optimum soil moisture (field capacity) (Wang *et al.*, 2006). Also even when temperature increases to above 5˚ C, corresponding to the time of application of N (end winter/ early spring) a negative net N mineralization can occur. This is attributed to the immobilization process due to a sudden high N concentration as a result of application of N fertilizers (Micks *et al.,* 2004). Therefore, this N pool is not readily available to the plants. It is hypothesized that microorganisms are better competitors than plants for the available N pools during early spring (Puri and Ashman, 1999; Recous *et al.*, 1992; Recous *et al.*, 1990). Apart from the possibility of leaching after harvest, autumns and winters are seasons when N loss happens (Engström *et al.*, 2011). From rosette stage up to stem elongation (before first application of N), there does not seem to be a clear pattern of mineralization, as there seems to be a decrease of air temperature in continental climates. Generally, mineralization of soil organic matters over winter in continental (D) Europe is quite low, and leaching occurs regularly (Henke *et al.,* 2009). Soil mineral N decreases over winter and there would be less differences in SMN in early spring among different sites and fields, but this difference is considerably higher by the end of autumn (Sieling *et al.*, 1999). Sieling (2000) explained a conflict in humid climate areas of Germany: SMN in early spring is quite low due to high plant uptake and high nitrate leaching in winter. On the other hand, in some other years or sites, SMN might be high in early spring due to low winter rainfall and cooler conditions, so that more investigations at different sites over a long period are essential. In general, indicators considering soil mineralization dynamics are not easily explicable for deciding on practical N application rates. Although the appropriate N prediction system is the one that predicts the highest possible yield, the optimum N- treatment varies with cultivar, year and site conditions, therefore, no general conclusion can be drawn (Rathke *et al.,* 2006). Timing of N application is mainly focused on spring; however, in continental climates, autumnal N application (30 kgN/ha only if required) can be defined for regions where mineralization is low. Yet, a higher autumnal N application rates reduce plant survival for winter, due to the higher susceptibility it causes to sudden frosts

(Rathke *et al.*, 2006). Spring N application mainly splits at two times; the first split is the beginning of spring re growth, and the second is the beginning of stem elongation. Notably splitting N application differs based on climate conditions and weather. Delayed N application in spring means a better probability for SMN contribution due to better temperature and lower precipitation, resulting in mobilization and higher N availability for crops in continental climates (Behrens, 2002). In addition, delayed N application at the beginning of stem elongation enhances apparent fertilizer efficiency, resulting in better N uptake at the reproductive phase. Generally, timing of spring N application is temporally oriented, and it is dependent on plant N demand, on a climate condition basis.

2.5.3. The effect of maritime/ Oceanic climates on growth, development, and N requirement

If considering the UK as a maritime/oceanic climate in the context of regions where WOSR is grown, the weather characteristics can be considered an average of both climates. Sowing date is suggested from about mid-August to mid-to-late September (Nutrient Management Guide (RB209)). This is due to the fact that the probability of frost damage, as it happens in Europe D climate, would not often occur in maritime climate. Shooting and flower bud emergence starts as temperature rises in spring, then roughly by mid-May, full flowering occurs for early sown crops. Harvest also will be mid to end July in these conditions. In UK studies the N uptake in November for WOSR sown in August is reported as 100 kgN/ha (Barraclough, 1989). Canopy in mild climates, as a result of no winter frost damage, can largely produce high biomass and N content. Hence, UK canopy management system would take into account the early spring GAI and crop N content, but, because SMN at early spring represents a snapshot of one time mineralization at the related site, more available N release is assumed from spring to harvest. This additionally available N is measured from 20 to 60 kgN/ha, depending on the existing SOM sources, soil temperature and C:N ratio (Blake-Kalff and Blake, 2014).

Wetter and warmer conditions between early spring and harvest in Ireland may describe probability for additional available N, based on site and year conditions for defining N requirement. The higher-than-the UK autumn precipitation increases the risk of poor plant establishment, slug, and/or pigeon damage. Owing to these issues as examples, farmers tend to apply a higher rate of N to compensate for poor canopy growth to avoid any yield penalty. Mild winters would enhance canopy sizes and more mineralization from spring onwards. According to Figure 2.11, one polar maritime air mass affects the Island of Ireland by bringing cold air and cold showery weather from Greenland and the Arctic sea, and another one, which dominantly can return this cold polar air mass via North Atlantic Sea and brings moist, mild and unstable rain showers and cloud coverage according to the Met office. Therefore, together with the knowledge of long term weather principles (rainfall, temperature, sunshine hours) (Figure 2.12), it is not known if a UK system of N prediction would also be applicable in Ireland, or if it needs an adjustment for this definition. Referring to the similar Figure (2.11), hot and dry air brings hot summers from tropical continental air masses and also from central Europe, then cold air and snow in winter comes from central Europe originating from polar continental air mass. Hence, it is possible to assume that winters are colder and snowy in the UK whereas it is milder in Ireland, as well as being wetter. Therefore, some variable factors such as post winter biomass accumulation and SNS need to be firstly examined in this region, as perhaps post winter canopy growth is significant in an Irish climate before considering N fertilizer application.

Autumn N application is omitted in these regions due to environmental reasons where leaching, and/or immobilization are probable, due to favourable soil temperatures of mainly > 6 ˚C during autumn and winter, where winter frost is uncommon. Nitrogen supply for early vegetative growth would be sufficient from mineralization of residual N from the previous crop in rotations (Rodgers *et al.*, 1986; Shepherd and Sylvester-Bradley, 1996).

The nitrates directive was established in the European Union (EU) in 1991 (OJEC, 1991). The legislation was set up as part of good agricultural practice for the protection of waters, to limit the use of fertilizers for the optimum yield results by reducing the amount of fertilizers, mainly N and P. The Nitrates Directive was implemented in Ireland in August 2006 under EU guidelines for the protection of waterways (Anon, 2006). Based on these regulations, fertilizer N recommendations in Ireland for WOSR have been generalized by only considering previous cropping history and a maximum application of 225 kgN/ha for soil N index 1 where the previous crop is either cereals or maize (EU Nitrate Directive Regulation, S.I. No. 605, 2017, gathered in irishstatutebook.ie). The maximum allowable figures are based on Irish fertilizer advice, where the only factors considered are the previous cropping and simple guidance on application of one third of the 225 kgN/ha to be applied in late February or early March and the remaining 2/3 in late March or early April (Coulter and Lalor, 2008).

2.6. Systems of N management of winter oilseed rape

2.6.1. General factors determining crop N requirement

Excess N fertilization results in economic loss due to yield reduction, and environmental pollution. Therefore, to make the correct decision on the rate and timing, it is important to consider both soil and plant. Nitrogen recommendation systems in many studies are based on a target yield; however, yield can be significantly different from one year or one site to another. Principles that are used to determine N application are not entirely predictable at the start of the growing season (Olfs *et al.*, 2005). For developing precise predictions, different methodologies have been improved based on measuring SMN that is mainly available to the plants at a given time; or also, plant- based analysis as a better indicator for the N supply from soil. Therefore, the required adjustment will be made for the most suitable N application strategy within a season, having soil mineral N and crop N as prerequisites for N application strategies. In this section, more details on soil-based and plant-based N recommendation systems will be summarized, including French, German, Chinese, UK and Danish systems, and the existing gap for an Irish N management system will also be evaluated.

Soil mineral N: there are several ways of measuring soil mineral N (SMN). Assessing SMN by salt solutions (Scharpf, 1977) such as KCl extraction with different rates of molarities is the most common approach that has been carried out for N recommendation as a general practice in older publications: i.e. in Canada (Soper and Huang, 1963) Sweden (N mmik, 1966) and the US (James, 1968). Also recommendations about the timing of taking soil samples or which layer depths to sample (i.e. German Nmin method) with the adjusted manipulations depending on circumstances: seasonal variations of mineralization (Herlihy, 1976), date of sampling (Herlihy, 1976), various pools which mineralization happens (according to previous crops) are only some of these examples (Juma *et al.*, 1984) and these make soil assessments vary.

In addition to methods for estimating SMN at only one general time scale, there are also methods that estimate the amount of N that will become mineralized during the growing season: laboratory incubation (aerobic and anaerobic N-mineralization tests) (Keeney, 1983), is based on the “substrate-induced respiration” method for calculating glucose decomposition of microbial biomass (Domsch *et al.*, 1979). However, these are restricted tests as each might have different results (Olfs and Werner, 1993). Generally, they might be restricted to research studies and are less practical on a field basis (Kitchen and Goulding, 2001), for example, a soil N test for predicting the released amount of N from temperate grassland soils was carried out in different regions of Ireland in which a 7-day anaerobic incubation procedure was used as a reference method. Despite the satisfactory accuracy, it was not advised as a practical method for the procedure needed dry soil with more than two weeks of measurement in climate conditions at a specific sampling time (Walsh, 2016).

Crop N content: plant material can be the best indicator of the N supply, as it reflects the N availability of soil and N uptake ability of the crop (Rice *et al.*, 1995). Plants` greenness (Früchtenicht, 1965) and visual assessments (Wollring *et al.*, 2001) have been of interest to track N content earlier than today, however, it is known that there are interactions between C and N balance involved in the photosynthetic process, which impact LAI, PAI and radiation use efficiency. Chlorophyll content resulting from greenness of the plant parts is a qualitative indicator. Studies have shown that there is a definite correlation between leaf N and chlorophyll concentration, so that the N status of the plants deriving from chlorophyll content can be used interchangeably as lab N analyses (Schröder *et al.*, 2000; Wood *et al.*, 1992). Today, there are superior ways of non-destructive, fast and efficient plant-based assessments, which can be site specific, or be based on optical measurements of canopy, namely, remote sensing (Lammel *et al.*, 2001). Chlorophyll a and chlorophyll b absorb the visible spectra of 400-700 nm. The next region, 700 to 1300 nm, known as the near-infra red domain, shows either reflectance or transmitted radiations (Guyot, 1990). When N is applied, chlorophyll content increases, and this leads to a higher absorption of the visible spectrum, and therefore an increase in near-infrared reflectance takes place when the plant is building up biomass. For detecting the variations of crop reflectance, the combination of reflectance are defined in two wavebands which are based on the chlorophyll concentration and some vegetation indices (Guyot *et al.*, 1992; Rouse Jr *et al.*, 1973) such as, Infrared-to-Red Ratio (IR:R), Normalized Difference Vegetation Index (NDVI), Soil-Adjusted Vegetation Index (SAVI) and Red-Edge-Inflection-Point (REIP). Devices for measuring these indices can be mounted on satellites, tractors, or be airborne (like drones), or be ground-based, etc., yet the suitability of each in different circumstances might not be the same (i.e. cloud coverage is a limiting factor for satellite-based devices) (VOß, 2004). Yara-N- tester™, satellite sensing services such as SOYL™ (in the UK), Farmstar colza™ (in France) use reflectance sensing. Other techniques for measuring crop growth and development to indicate crop N dynamics include radiation interception which measures light-intercepted by a canopy: Delta-T™ Sunscan.

An estimate of the green area of a crop can be achieved based on image analysis using smart-phone app or online tools (https://www.agricentre.basf.co.uk/en/Services/Online-Tools/OSR-GAI-Online/). These methods needs to be calibrated under field conditions, so that the optimum N rate and timing of fertilizer application can be reliable (Olfs *et al.*, 2005).

Soil N Supply (SNS): Spring SMN + Crop N content is the amount of N from the soil that has become available to the crop. It is calculated from the available N through mineralization or any residual availability from soil nitrate or ammonium that is taken up by the plant over the growing season. SNS does not include the amount of N fertilizers or manure N; therefore, the best estimation of total SNS is the amount of N taken up by the unfertilized crops in the UK studies (Kindred and Sylvester-Bradley, 2014). For WOSR in particular, estimation of crop N is as important as soil N, because the crop is able to take up more than 100 kgN/ ha over the winter, while in wheat crops this uptake rarely rises up to 30 kgN/ha (Kindred and Sylvester-Bradley, 2014).

As a general view, analysis of SMN at the beginning of the growth period is a routine practice for deciding on the N application rate. In the UK, which will be discussed later, SMN is a part of the soil N supply index calculation which is adjusted according to previous crop, soil type and over-winter rainfall. In France and Germany, SMN is based on a balanced approach in which several parameters of N supply from soil and atmosphere and even N losses are considered (COMIFER, 1996).

2.6.2. Balance sheet method

Balanced fertilization was set out following the nitrates directive (EC, 1991) regulations, as the application of N fertilizers should be in a balanced manner between the N requirements of the crops and the N supplied through the soil and fertilizer. The balance sheet method was developed by Reau *et al*. (1994) and Reau and Wagner (1998), in which the calculation of mineralized soil- borne N and the N in the OSR canopy by the end of autumn and the end of winter were calculated. The N uptake requirements during the balance sheet period can be defined as the difference between the taken up N at harvest and the crop N at the start of the period (mid- January to mid -February) based on a yield target. It can vary from 20 to 300 kgN / ha in various regions of France. When using this method all N sources of SMN available to the crop, the taken up N and the N losses during this period are assessed. This system is used with the same underlying principles of calculation for the French website 'regulating N for winter oilseed rape' as a farmer-friendly approach (regletteazotecolza.fr/#/etape1). Therefore, the N requirement prediction (based on a yield prediction system) follows the below equation:

The harvest N uptake as a proportional to the yield = yield in quintal[1] *(qu)/ha (for seeds with 2% impurities and 9% water content) × 7 (210 kgN / ha for a yield of 30 qu / ha)*

The required amount will be maximized at 330 kgN / ha (beyond this, the yield is no longer limited). So that:

The required N fertilizer in the spring = N uptake requirement + N losses from the crop - N supplies to the crop

Depending on which part of France WOSR is grown in, the crop N might be bigger or smaller in early spring compared to early winter. If crop N were larger in early spring than early winter, plant N uptake would be calculated as early spring (meaning insignificant leaf loss over winter). If crop N in early spring was smaller than early winter (meaning more leaf loss over winter) then the equation below is taken into account:

[1] One quintal equals 100 kg

If spring crop N < autumnal crop N then, = N uptake at early spring + (0.5 (Autumnal N uptake –Spring N uptake) / 1.35

The 0.5 (50%) value is the amount of assumed recycled N, which will appear later in the crop; and the 1.35 is the calculated coefficient of N loss in aerial parts (Justes *et al.*, 2000) (Champolivier, Email communication, April 01, 2020).

Therefore, a farmer`s approach using the website (regletteazotecolza.fr) for crop N calculation using Fresh Matter (FM) weight would be;

N content (kgN/ha) (in autumn) = FM (autumnal canopy) ×50

N content (kgN/ha) (in spring) = FM (spring canopy) ×65

The German N fertilizer calculation is based on growth stages (Rathke *et al*., 2006); where SMN use was also taken into account at the beginning of spring. This was firstly developed by Wehrmann and Scharpf (1979) for winter wheat under the name of N_{min} method. Henke *et al.* (2009) on north side of Germany tested whether it was SMN and canopy N in early autumn or in early spring that should be taken as an accurate estimator of the spring optimum fertilization rate (N_{opt}). Their regression analysis showed variations were significantly explicable by a negative correlation between canopy N and soil mineral N in autumn rather than that in spring (Henke *et al*., 2009). Authors suggested that autumn canopy and SMN are better predictors for calculating N fertilization rate in spring, notably if the crop N content was >50 kg N/ha (small leaf loss).

Similar to French studies, N content estimation in the canopy during autumn could also be simplified using fresh weight materials (kg/m^2) by multiplying a conversion factors of 45 for autumnal canopy and 54 for spring canopy N (kg/ha). Higher N content in spring resulted in the higher correction factor of 54. It is noteworthy that the coefficients are different for autumn and spring between the two countries.

Authors discussed that the OSR crops normally expect a recovery of N loss due to leaf loss over winter in spring of about 40% under European climate conditions at different years and sites (Dejoux et al., 1999). Dejoux et al. (2003) had also reported that the large variations in canopies in autumn would decrease after winter. Hence, N fertilization rates might be overestimated if canopy N in spring is taken into account (Henke et al., 2009). Conversion factors were based on the assumption that above ground dry matter and N content vary a little during early growth stages, describing critical N dilution curves in 2.5.4.2 section (N content % is constant for shoot dry matter of up to 1 t/ha).

2.6.3. Chinese Study Approaches

The common location of winter oilseed rape in China is mostly in mid and low-basin of Changjiang- (Yangtze River Basin). October is the common sowing date and May is the time of harvest (Clever *et al.*, 2015). Soil Indigenous N supply (INS), which is a similar concept to SNS, is evaluated from various physicochemical soil properties such as SOM, NH_4^+, SMN, alkaline hydrolysable-N, and also plant indicators, namely, N uptake under zero fertilizer and crop yield, etc. (Adhikari *et al.*, 1999; Cassman *et al.*, 1996; Li *et al.*, 2010b; Wang *et al.*, 2012; Waring and Bremner, 1964). In the case of China, soil conditions and cultivation methods change from farmer to farmer; as winter oilseed rape is in a single or double rotations with rice, cotton, and other summer crops (Li *et al.*, 2015); therefore, the frequent alteration between wetting and drying cultivation methods would cause SMN and SOM to be different. Some studies have attempted to demonstrate a relationship between soil properties and the relative yield through the INS system. Results mainly showed a failure to find a relationship between soil properties and the relative yield. Many authors suggested that various soil types, climate conditions, and planting methods across the sites are the main reasons for variations and a lack of a clear predictable relationship. They also discussed the fact that cultivation methods in China follow a small-scale model (i.e., per capita arable land of 0.1 hectares) in comparison with the farming model of e.g. Canada, Australia, and America with per capita arable land of 1.3, 2.0, and 0.3 hectares, respectively, according to FAO, 2013.

In a study by Ren *et al.* (2015) the use of INS helped the local N recommendation reach closer to the economic optimum N fertilizer rate when comparing two different crops (rice and cotton) in rotation with WOSR. The finding was related to the fact that higher N loss, run off and ammonia volatilization in rice cultivation is more probable, therefore, the residual mineral N in the soil decreases after harvest. Owing to INS values coming from the two different crop groups, a slight increase, and a decrease of N rates respectively for rice-WOSR and cotton-WOSR was suggested as a change in the local N recommendation values for maintaining NUE and yield in their economical optimum ranges.

Another system of N management was based on the Apparent Nitrogen Balance (ANB) concept (Duan *et al.*, 2014; Vitousek *et al.*, 2009; Yadav *et al.*, 2002), meaning that the applied N should be reduced from the total N uptake at maturity to calculate the balance between crop N demand, N supply, and also the N loss to the environment. Yousaf *et al.* (2016), in the region of Yangtze River conducted an experiment on two seasons of rice-oilseed rape rotation. This was to evaluate the effect of different N application rates on N use efficiency (NUE) and ANB in the centre of China. Results demonstrated that using ANB, NUE and yield together would lead to the optimum N application rate decision in the two-year rotations. The N rate of 180 kgN/ha was sufficient to meet the optimum yields for rice-WOSR crops with the ANB of 234 kgN/ha during the total rotation, with an increase of 156% in WOSR yield comparing to zero N control treatment. Authors concluded that the appropriate N management strategy can be developed using ANB, NUE and yield for rice-WOSR rotation in central China.

2.6.4. Canadian approach

Studies demonstrated that different N application strategies on the west and east sides of Canada are important to consider. For example, the side-dressed N application at the 6 leaf-stage increased canola yield in the west compared to the equivalent amount of N entirely at pre-plant level in the more humid eastern side of Canada (Ma, *et al*., 2015). Also in western Canada, under arid and semi-arid conditions, splitting N applications between the seeding and rosette stages did not make any difference compared with application of all N at seeding (Grant *et al*., 2012). It was suggested that in the eastern part of Canada, N application needs to be defined based on in-season application similar to maize and wheat (Ma *et al*., 2005, 2006, 2007). Therefore, in a study by Ma, *et al*., (2016), in eastern Canada, N was applied as urea (46% N) and application timing was split as pre-plant, and pre-plant plus top-dressing at 6 leaf stage. Results demonstrated that seed yield increased by 16% for side-dressing when the N rates were 50 + 50 kg N/ha and also 50 + 100 kgN/ha (pre-plant + side-dressing) due to higher partial N balance.

In another study the importance of N fertilizer adjustment rate in canola based on the pre-ceding crops (legumes) was examined to minimize the potential for N losses (Luce, *et al.*, 2016). The apparent in-crop N mineralization (ANM) was calculated (kgN/ha) for the control treatments as the difference between N recovered at harvest and N supplied at planting using the equation:

$$ANM= (N_{out}+ N_{min\ harvest})- (N_F + N_{min\ planting})$$

Where N_{out} was the total above ground plant N uptake, $N_{min\ planting}$ and $N_{min\ harvest}$ were the soil NO_3-N content of 0-60 cm soil at planting and harvest, respectively, and N_F was the starter fertilizer N applied. Hence, the calculation of N budget which was separately carried out for the canola and wheat crops considered N inputs from soil (0-60 cm depth) and fertilizer N applied and the N outputs (above-ground N uptake). The assumption was based on the fact that the pre-plant soil NO_3-N and the N from ANM were available to be taken up by the plant and were consistent among treatments of the study. Therefore, the estimation of the proportion of plant-available N that was taken up was distinguishable while the other N sources (fertilizer or mineralization) were not taken into account. Subsequently, apparent N fertilizer uptake efficiency and the economic optimum N rates were calculated for the study. Results of Luce, *et al*., (2016) study showed that in no-till soil systems, the above-ground residue N returned was greatest on legumes but lowest for oilseed rape and wheat. Also, apparent ANM under oilseed rape was greater following Faba beans. The N budget demonstrated that 40-65% of the crop N uptake was possibly derived from ANM more so following legumes rather than 35-60% from fertilizer. The surplus N and unaccounted N (i.e. leached N) were more pronounced when oilseed rape and wheat were preceded by legumes rather than oilseed rape and wheat, hence, legumes was suggested valuable for enhancing soil N supply in no-till soils.

2.6.5. UK approach

Fertilizer recommendations for crops in the UK are gathered in Defra publications. They were originally referred to as the Fertilizer Manual Reference Book 209 (RB209) (Defra, 2010); but are now published by AHDB and are known as the Nutrient Management Guide. There are three major components that fertilizer N recommendation is based on: firstly, crop N demand, which is the amount of N that the crop needs to optimize yield, secondly, SNS, which is the amount of N available from the soil, and finally, the proportion of applied N fertilizer that the crop takes up, as per the equation below (Sylvester-Bradley *et al.*, 1998):

$$\text{Nitrogen Requirement (kg N/ha)} = \frac{Crop\ N\ Demand - Soil\ Nitrogen\ Supply}{Fertiliser\ N\ recovery\ (\%)} \quad \text{Eq.2.7.}$$

Crop N Demand prediction: plants need N to build up green canopy structures, and to intercept enough light to achieve an optimum yield. Optimum canopy size in WOSR at flowering was measured to be 3.5 unit of GAI when the targeted yield is at least 3.5 t/ha in UK climate conditions (Berry and Spink, 2009). For building up 1 unit of GAI, oilseed rape requires 50 kgN/ha (Lunn *et al.*, 2001), then, 175 kgN/ha is needed to achieve the optimum size of the canopy (3.5×50) until the critical point of flowering. Crop N demand, however, is not restricted only to build up canopy. The economic N rate rises by 50-60 kgN/ha for one additional tonne in yield as an adjustment for a higher yield potential per hectare (Berry *et al*., 2011; Holmes and Ainsley, 1979). This means for an adjustment of 1 t/ha yield over 3.5 t/ha, an extra 60 kgN/ha in fertilizer rate is required.

Apparent Fertilizer N recovery %: Fertilizer recovery is assumed to be 60% on most soils, 70% for silty/sandy soils, and 55% for shallow over chalk soils according to the UK fertilizer manual (AHDB Nutrient Management Guide). The assumption for oilseed rape was as mentioned previously, that OSR is able to take up 100% of soil mineral N + Crop N measured in February, with 60% of N fertilizer applications on most soils; these average figures of N uptake efficiencies are presumed to be similar to wheat experiments (Berry and Spink, 2009; Stokes *et al.*, 1998; Vaidyanathan *et al.*, 1987). Nevertheless, the recovery percentage of fertilizers varies considerably between N response experiments and fertilizer types and it is not predictable (Sylvester-Bradley *et al.*, 2014).

The principles of canopy management as described before can be finalized in the equation below specifically for winter oilseed rape, and can also be adjustable for >3.5 t/ha of yield by applying more 50-60 kg more N /ha at yellow bud.

$$\text{Fertilizer N Requirement (kg N/ha)} = \frac{Crop\ N\ uptake\ Target\left(175\,\frac{kgN}{ha}\right) - Soil\ Nitrogen\ Supply}{Apparent\ Fertiliser\ N\ recovery\ (0.6)} \quad \text{(E.q. 2.8.)}$$

2.6.6. Denmark

Denmark uses a fertilizer balance system successfully (Smith *et al*., 2007; Mikkelson *et al*., 2009). There is an obligatory plan to limit the amount of N application on various crops (Mikkelson *et al.*, 2009). In this country SMN is used to provide an “N-prognosis” in each spring around the whole country, and as the country is subdivided into three climatic parts and four soil types, N recommendations are announced according to these regions (Olfs *et al.*, 2005). The related studies showed that NUE has increased and N losses have decreased.

2.6.7. Ireland

As mentioned earlier, N application rate is a generalized scale, categorized by soil N index systems (Coulter and Lalor, 2008). It is noted that a recent study has shown that the soil N index system was only capable of describing 20% of the variations in N supply across 110 sites in Ireland from 2012 to 2014 (Walsh, 2016).

On the other hand, crop N requirement depends on 1) N demand, 2) available N from other sources than N fertilizer, and 3) fertilizer N efficiency uptake (Appel, 1994) which differ on a site- year basis. Hence, there seems to be a requirement for bridging the gap between more precise N requirement predictions for WOSR in Ireland. For this purpose the closest possible principles in terms of N application on more alike climate (with slight differences) is the UK CM system for which each of the principles need to be tested.

2.7. Summary and final comparisons

Increasing WOSR N prediction precision, evidently, seems to be an on-going under re-search procedure, for there are many sources of variations associated with leaching, continued crop N uptake and mineralization, atmospheric N inputs, immobilizations, continuous break-down of crop residuals, cultivation-enhanced mineralization, spatial and temporal variabilities (Sylvester-Bradley, 1992). Hence, N prediction systems cannot be generalized or be advised as one-size-fits-all, as measurements might well be spatially-temporally different from each country, region, year, site, etc. Examples from French studies were shown if end autumn or end winter canopies are taken into account, the recycled N% can be different as these values are quantified through crop modelling. Then based on seasonal canopy, a correction factor can be multiplied to the fresh weight of the plants. Moreover, Farmstar colza™, a satellite-based remote sensing system used in France enables identification of the heterogeneity at plot level in terms of LAI, or chlorophyll content at specific growth stage and therefore, application of N would be justified based on the target yield. Other countries such as UK, Germany, Spain, Canada and Australia also have considered satellite-systems (Coquil *et al.*, 2005). Germany, also, takes into account a regional approach, which according to the growth stage based on degree growing days and meteorological data accurate N application rates are suggested.

Yet, the consistent problem among all N prediction studies, taking into account SMN before spring N applications, is its variability. Although it is known as a necessary-to-include indicator, it is not satisfactory, and considered a 'black box' where the amount of N that becomes available through the season is unknown (Grzebisz *et al.*, 2018; Łukowiak and Grzebisz, 2020).

Factors that are used in N prediction systems should eventually be regionally calibrated, cost-effective and farmer- friendly and practically possible. Farmstar colza, for example, is a satellite-based system of assessment, which works best in a clear sky (no cloud coverage) mainly during winter/ early spring. Soil N supply measurements also cannot be done on each site-year basis, nevertheless, extra available N during the growing seasons is still considered.

Briefly, the situation for defining an N application system on WOSR in Ireland seems like a progress, from general scale to a further optimization using three major principles from UK CM approach. Hence, a study is needed to bridge the gap between crop N demands, soil N supply, fertilizer N uptake efficiency, and better yield profit.

3.0. The impact of sowing date on soil mineral nitrogen (N) uptake efficiency and fertilizer N uptake efficiency for winter oilseed rape (*Brassica napus* L.) in a mild climate

3.1. Abstract

Currently recommended application of N for winter oilseed rape (WOSR) in Ireland only considers limited determinants, such as previous cropping history of the site. In the UK, where the climate in the WOSR growing areas is generally drier and colder in winter, crop fertilizer requirement is based on a canopy management (CM) that takes N in the soil and crop post-winter into account. This research assessed the UK CM approach in Ireland by testing soil N uptake efficiency (SNUpE) and fertilizer N uptake efficiency (FNUpE%) at different sowing dates and comparing these values to the UK studies. Based on UK-CM principles, SNUpE is assumed 100% of N uptake efficiency over winter growth and FNUpE% is estimated as 60% on most soil types. To test these values, three-years of field trials were carried out on three site-years, using a split-plot experimental design. Three sowing dates (SD): mid-Aug (SD1), End-Aug (SD2) and mid-Sep (SD3) with N application strategies; based on UK-CM principles (CMStd, CMHiY and CMLoY), Fixed N rate (225 kgN/ha) and a zero-N control were all set at subplot level. Results from ratios of final N uptake and spring SMN plus crop N on zero-N plots showed SNUpE was > 1 (or > 100%) on all SDs: 1.14 for SD1 and SD2, and a significant value of 1.65 on SD3. Average FNUpE% reduced as SD delayed across N strategies, with 47.1%, 42.7% and 37.5%, respectively from SD1 to SD3 on all site-years. Fertilizer NUpE% was lower than the 60% of the UK assumption. Super-optimal N rate of >200 kgN/ha from CMHiY and Fixed 225 reduced the efficiency of fertilizer N uptake by 10 to 20% across SD×N in site-year 1, site-year 2 and site-year 3/SD3. When regressing different N strategies against yield, optimum N rates (Nopt) proved that, the closest N strategy to the Nopt was CMStd in year 1 and year 2 with maximum FNUpE% of 55% in year2/SD1. Also, CMHiY with N rate

of ≤ 200kgN/ha in site-year 3 in SD1 and SD2 was closer to the 60% UK CM assumption. Understanding that SNUpE was higher on late SDs but less efficient than 60% of FNUpE implies the necessity of an adjustment from the UK-CM on late sown crops or an avoidance from sowing at very late timing where possible.

3.2. Introduction

Winter OSR (*Brassica napus* L.) is an important broadleaf crop used in cereal rotations bringing benefits in disease, pest and weed control and therefore yield increases (Hegewald *et al.*, 2018; Kirkegaard *et al.*, 2008; Kirkegaard *et al.*, 2016; Morrison *et al.*, 2016; West *et al.*, 2001). In Ireland, 9.5% of the agricultural area is under the cultivation of annual crops, of which only 10.3% is used for non-cereal in rotations (Central Statistics Office, 2020). Winter OSR, is well-suited to the Irish climate, with yield potential of up to 6 t/ha, a succeeding booster in cereals rotations, with national and international markets for oil and protein cake according to CROPQUEST report (Teagasc.ie/ OSR, 2020). The crop is high-N demanding, and able to take up large amounts of soil mineral N (SMN) before the onset of flowering (Aufhammer *et al.*, 1994; Barraclough, 1989). Therefore, mineralization can hugely affect crop`s N uptake considering that decomposition kinetic ranges are dependent on soil temperature and moisture for net N mineralization (Gilmour, 1998; Terry *et al*., 1979). Nitrogen use efficiency (NUE) of the crop is defined as the harvestable dry matter (DM) yield (t/ha) divided by the supply of available N from both the soil and fertilizer (kg/ha) (Moll *et al.*, 1982). It is important to keep NUE as high as possible so as to reduce the environmental impact and N losses (Sieling and Kage, 2006; Storer *et al.*, 2018). Improving NUE is complex but achievable by: 1) reducing N requirement while maintaining yield, or 2) increasing yield without increasing N requirement (Sylvester-Bradley *et al.*, 2015).

In Ireland, mild weather with high OM levels in soil increase the likelihood of higher N availability release during the growing season (Humphreys, 2007). Despite this variability due to weather and soil conditions, N application advice is based on limited parameters on WOSR. A soil index system for N is determined by considering previous cropping history of the site as a basis for nutrient advice, which is implemented through S.I. 605 of 2017 and presented in Teagasc major and micro nutrient advice for productive agricultural crops (Wall and Plunkett, 2016). Therefore, a more comprehensive system of applied N strategy is required to include soil and crop N content before application of N fertilizer on a site-year basis scale. This requires a knowledge on synchronization of the crop N demand, soil N supply and fertilizer N uptake efficiency (FNU$_P$E) improvement (Yousaf *et al.*, 2016).

Sowing date of this crop is chosen on the basis of optimizing growth and development for different environmental conditions (Dejoux *et al.*, 2003). In continental Europe early autumn sowing dates may correspond to dry conditions (Pouzet, 1995), or later sowing dates may not allow adequate growth for winter survival (Merrien and Pouzet, 1988). In conditions where significant winter frost occurs, WOSR is sown from 20th August to 10th September, and if it is sown closer to mid-Aug, nitrate leaching will be reduced as the plants N uptake capacity in autumn is very high (Dejoux *et al.*, 2000). Delayed sowing date (up to mid-Sept) has a modest effect on seed yield in UK due to continental-maritime climate (Leach *et al.*, 1999), whereas reduction in yield was reported in northern Germany (Sieling *et al.*, 2005).

To-date, there have been no studies conducted in a mild Atlantic climatic region like Ireland which considers soil (SNUpE) and fertilizer N uptake efficiencies (FNUpE) as factors for defining crop N requirement on various sowing dates and crop sizes particularly on WOSR. Although there had been examples of N prediction systems taking into account soil N tests for increasing N use efficiency and thereby reducing N loss in mild but humid conditions in Maryland using pre-planting soil nitrate tests on winter wheat (Forrestal *et al.*, 2014) or pre-side-dress soil Nitrate tests (PSNT) (Meisinger *et al.*, 1992).

N fertilizer recommendations for different crops are based on estimates of 1) crop N demand, 2) soil N supply (SNS), defined as the crop N uptake without N fertilizer and 3) FNUpE%: the percentage of (the apparent) fertilizer N uptake efficiency (Appel, 1994). Nitrogen recommendation based on the aforementioned factors for the UK is described in the AHDB Nutrient Management Guide (RB209) (www.AHDB.org.uk), underpinned by research on the principles of Canopy Management (CM) in cereals (Sylvester-Bradley *et al.* 1998) and WOSR (Lunn *et al.* 2001; Berry and Spink 2009; Berry *et al.* 2011). The principles that these systems are based on for WOSR include: 1) the crop must achieve an optimum canopy size (indicated as green area index,GAI) by flowering when each GAI unit contains 50 kg N/ha; 2) all SMN and crop N uptake at the start of stem extension is assumed to contribute to the N demand of the crop, defining soil N supply (SNS) (Kindred and Sylvester-Bradley, 2014; Sylvester-Bradley *et al.*, 1998); and 3) N fertilizer is assumed to be taken up with an efficiency of 60% on most soil types. Also, 4) potential high yielding crops would require additional N fertilizer at a rate of 60 kg N/ha per additional tonne of seed to obtain an estimated expected yield of 3.5 t/ha (Berry *et al.*, 2011; Holmes and Ainsley, 1979).

While the UK has the closest maritime climate to Ireland, it is not known whether the CM system for estimating N fertilizer prediction is appropriate for the Irish environment, which tends to have milder winters. It was considered valuable to test the principles that underpin the UK-CM approach to potentially adapt and improve them for Irish conditions. Therefore, the aims of this work are to determine: 1) if soil and fertilizer N uptake efficiencies are different in Irish climate compared to UK and other European WOSR growing regions, 2) if sowing date influences soil and fertilizer N uptake efficiency in the Irish climate, and 3) the amount of additional available soil N (AAN) that releases through the growing season (after early spring SMN measurements) on unfertilized plots.

3.3. Materials and Methods

3.3.1. Experimental sites and N strategies

Field experiments were carried out over a three year period at Teagasc, Oak Park- Carlow, Ireland (52°51‘40” N, 06°54’55’’ W at 62 m above sea level). The WOSR trials were on different sites each year and were preceded by winter barley in a continuous cropping rotation. Site details are given in Table 3.1.

Table 3.1. Detailed characteristics of each year-site

Site- year	Soil Texture*	Soil pH	Soil organic matter %	Sowing Dates (SDs)	Date of GAI measurement and SMN sampling
Year 1 (2017-2018) Bull Park	Loam	7.1	4.4	SD1: 18.08.17 SD2: 31.08.17 SD3: 19.09.17	Mid- Feb.
Year 2 (2018-2019) Church Field	Loam	7.4	5.3	SD1: 15.08.18 SD2: 28.08.18 SD3: 14.09.18	Mid-Feb.
Year 3 (2019-2020) Malone’s Field	Loam	7.2	4.6	SD1: 15.08.19 SD2: 28.08.19 SD3: 20.09.19	Late Feb.

* USDA textural soil classification

The split-plot experimental design had the main plots as sowing dates (Mid-Aug, End-Aug, Mid-Sept) randomized in 4 replicate blocks. Also, N management strategies were randomized at subplot level with the dimension of sub-plots being 21 m × 6 m. Conventional crop establishment was carried out; plots were ploughed at a depth of 225 mm, then a power harrow cultivated to a depth of 100 mm with a 3 m seed drill. Seed row spacing was 125 mm with a seeding rate of 50 seeds /m^2 of the conventionally bred variety, Anastasia. The N management strategy treatments are outlined in Table 3.2 and include zero-N controls in all years. Calcium ammonium nitrate (CAN, 27%) was used as the N fertilizer for all experiments and was applied to individual plots using a full-width plot applicator. All other crop inputs such as pesticides, herbicides, fungicides and nutrients other than N were applied according to the WOSR reference guide (Teagasc Crop Report, 2019) to prevent factors other than N limiting yield.

3.3.2. N strategies and CMs

Fixed N levels and various canopy management N strategies were used in the trials (Table 3.2.). Fixed 225 kgN/ha is the recommended value for an index 1 soil, where the previous crop is either cereals or maize according to "Major and micro nutrient advice" (Wall and Plunkett, 2016). For the CM approaches, spring soil nitrogen supply (SNS) was calculated from estimates of crop N (from GAI) and soil N (SMN) before the onset of spring growth. The standard CM, (CMStd), was an estimation of N that is required for the plant to achieve 3.5 units of GAI. According to the CM, each GAI unit contains 50 kgN/ha, therefore, 175 kgN/ha can at least target a seed yield of 3.5 t/ha by flowering. A high yielding CM treatment, CMHiY, had an extra 60 kgN/ha more than CMstd which was applied at yellow bud stage to support a seed yield of 4.5 t/ha. Finally, a CM using less N, CMLo was arranged by considering 125 kgN/ha as crop N demand by flowering as opposed to 175 kgN/ha, and was applied in years 2 and 3.

Table 3.2. N application strategies, timing, and their resulting N application rates

N Strategy	Year1 SD1	Year1 SD2	Year1 SD3	Year2 SD1	Year2 SD2	Year2 SD3	Year3 SD1	Year3 SD2	Year3 SD3	N proportion and timing*
	N application (kg N/ha)									
Fixed225	225	225	225	225	225	225	225	225	225	0.33 before stem extension/ 0.66 early green bud
CMHiY	170	225	260	224	205	200	200	187	261	as above +60 kgN/ha at yellow bud
CMStd	110	165	200	164	145	140	140	127	201	0.33 before stem extension/ 0.66 early green bud
CMLo	-	-	-	81	61	57	56	44	118	
Zero-N	0									

* Depending on weather conditions in early March to early April, N rates split more than two proportions within maximum two weeks interval.

3.3.3. Measurements

3.3.3.1. Crop establishment and post-winter measurements

Plants were counted to determine establishment in all of the main plots (6 counts of 0.5 m^2/ plot) at two-week intervals following emergence until full establishment for each different SD. Above-ground plant sampling was used to measure biomass and GAI with two 0.5×0.5 m^2 grid on each subplot. A 20% subsample of plant components (leaf and stems) was scanned for measuring the green area using a Delta-T leaf scanner, (winDIAS, Cambridge, UK). Additionally, a GAI estimation based on in-field image analysis through the BASF™ online tool services website was used to calculate post-winter GAI for the estimation of SNS before N application. Photos were taken in 6 replications for each subplots at different SDs, and were uploaded to the website to estimate a GAI for each sowing date. Growth stages were defined using the growth stage system of BBCH (Lancashire *et al.*, 1991) coding system by counting leaf number and measuring plant heights. Total biomass weight of the separated plant components; leaves and stems (and pods from GS 79 to GS 85) was also calculated (as the sum of all plant fractions). In site-year 2 and 3, depending on weather suitability for sampling. Soil samples were in four replications at three SDs and at three depths 0-30, 30- 60 and 60-90 cm were taken separately in early spring (February). Mineralized N was analyzed according to NO_3-N (mg/kg) and NH_4-N (mg/kg) content using KCl- solution extraction (Scharpf and Wehrmann, 1976). In site-year 1, SMN was sampled in four replications at three depths, to give an average figure for the whole site, but not by individual sowing date.

3.3.3.2. Crop N at harvest

As harvest approached and seeds changed colour to brown, pre-harvest sampling was carried out using a 1 m^2 grid in each plot prior to desiccation. Plants were cut at stem-base level and counted in the field. Next, a 20% subsample of plants was selected for weighing stems, leaves and pods separately for biomass. All non-pod material was chopped and subsampled for DM analysis. Pods were sub-sub sampled for counting and yield component measurements, then were dried for calculating DM. Pod walls were then separated from seeds. A ratio of pod wall and seed weight, and stem to seed weight were taken into account for precise final biomass calculation. Analysis of N content of all dried plant components and ground plant fractions was performed by Dumas analysis (Rapid N Cube, Elementar Analysensysteme, Hanau, Germany). Field desiccation with glyphosate reduced seed moisture from circa 30% moisture content (at GS 85 to 99) to an estimated 10% at harvest. Late sowing date crops were desiccated on a later date based on seed maturity. A 2.75 m wide full plot length strip was harvested from each plot using a plot combine harvester (Deutz Fahr 37.10), with an extended header and vertical cutting bars at both sides. Seed yield was calculated in t/ha at 91% dry matter using the plot length and combine head dimension, and seed weight per plot.

3.3.4. Calculations and Statistical analyses

Soil mineral N Uptake Efficiency (SNUpE) was measured on unfertilized plots (zero-N), and calculated from the total N uptake at harvest as the seed, straw and pod wall N expressed as kg/ha. The sum of early spring-measured crop N and SMN was used to include the concept of soil N supply (SNS) (Eq. 3.1).

$$SNUpE_{\text{(Zero-N Plot)}} = \frac{\text{Total N uptake}}{\text{Crop N in spring} + \text{SMN in spring (SNS)}} \qquad \text{(Eq.3.1.)}$$

To measure the apparent fertilizer N uptake efficiency (FNU_PE), total N uptake from unfertilized plots was subtracted from the total N uptake in fertilized plots and divided by the specific N fertilizer rate (Eq.3.2.).

$$FNU_PE\ \% = \frac{\text{Total N uptake(fertilized plots)} - \text{Total N uptake(unfertilized plots)}}{\text{Fertilizer N Rate}} \times 100 \qquad \text{(Eq. 3.2.)}$$

Data was analysed using Genstat 19.0 separately for each site-year (Year 1, Year 2 and Year 3) and also across years. . A split-plot ANOVA analysis was used for which sowing date counted as main plot, with N strategies (sub-plot), were considered as fixed factors when calculating on individual years, while blocks were considered as random factors. ANOVA analysis across years had blocks and site-year effects as random factors as the main focus was on the effects of N strategies and SDs. Heterogeneity of variance of all analyses caused by different sowing dates and site-years were included but no uniform standard error could be given; consequently, Bonferroni paired mean difference analysis was applied. Analysis was conducted for each individual year, and across three years for the core set of common N strategies including: Zero N, Fixed 225, CMStd, CMHiY and additionally CMLo for Year 2 and Year 3.

Yield and N rates determined by N strategies were regressed using linear plus exponential (Lin+expo) curves (George, 1984), at separated years, and also grouped by SDs (Equation 3.3).

This was done, to determine the economic optimum N rate (Nopt) to distinguish the best FNUpE% value on its N rate.

$$Y= A+ BR^{N}+ CN \quad \text{(Eq. 3.3.)}$$

Where Y is the yield (t/ha), "A," "B," "C" and "R" are fitted constants, and N is the nitrogen value. A stepwise regression process was followed for each year in four steps: 1) fitting a common curve on all SDs, 2) fitting separated parallel curves for each SDs with the same slopes, 3) fitting separated curves for each SDs (similar intercepts), and 4) fitting separate curves for each SD by allowing all parameters to vary. The sum of squared error was used at each stage to assess for an improvement of fitting over the previous model, and if there was no significant improvement, between two stages, the previous stage was taken as the best fitted lin+expo model. The economic optimum N rate (Nopt) was then used as a deviation from Eq.3.3 (Eq. 3.4).

$$Nopt= \frac{[\ln\left(\frac{K}{1000}-C\right)-\ln\left(B(\ln R)\right)]}{\ln R} \quad \text{(Eq. 3.4.)}$$

K is the breakeven ratio, calculated as a ratio between fertilizer N (price/kg of N) and seeds (price/kg of seed). A breakeven ratio of 2.44 was used in this study as an average value of eight years (from 2011 to 2018) in Irish market (Eq. 3.5.)

$$K \text{ (break-even ratio)} = \frac{\text{N fertilizer cost}\left(\frac{€}{\text{kg N}}\right)}{\text{Seed price }\left(\frac{€}{\text{kg N}}\right)} \quad \text{(Eq.3.5.)}$$

3.4. Results

3.4.1. Weather data

Figure 3.1. summarizes the precipitation and temperature patterns during years from 1981 to 2010 as Long Term Average-Rainfall (LTA-R) and Temperature (LTA-T) together with weather conditions during the three years of the experiment at Oak Park (Met Eireann).

In site-year 1 (2018), from mid- autumn (September) to spring, rainfall above LTA-R was recorded following a higher temperature than LTA-T in May, June and July. A summer drought with the lowest rainfall since 1850 was experienced in Ireland during summer 2018 (Met Eireann).

In year 2, rainfall above the LTA-R occurred during November and December (average: 140 mm), followed by drier January and February (35 mm), with temperature being above LTA (6 to 8˚ C) during these months. This was followed by a wet period with (on average) 100 mm of rainfall in March and April, whereas May was the driest month of that year (18 mm).

Similarly, rainfall was above the LTA-R in autumn of year 3, causing a delay in the 3rd sowing date. November was slightly colder than normal, and was followed by a February rainfall spike of >170 mm with a subsequent slightly warmer than average temperature in spring and summer of 2020 (>6˚C).

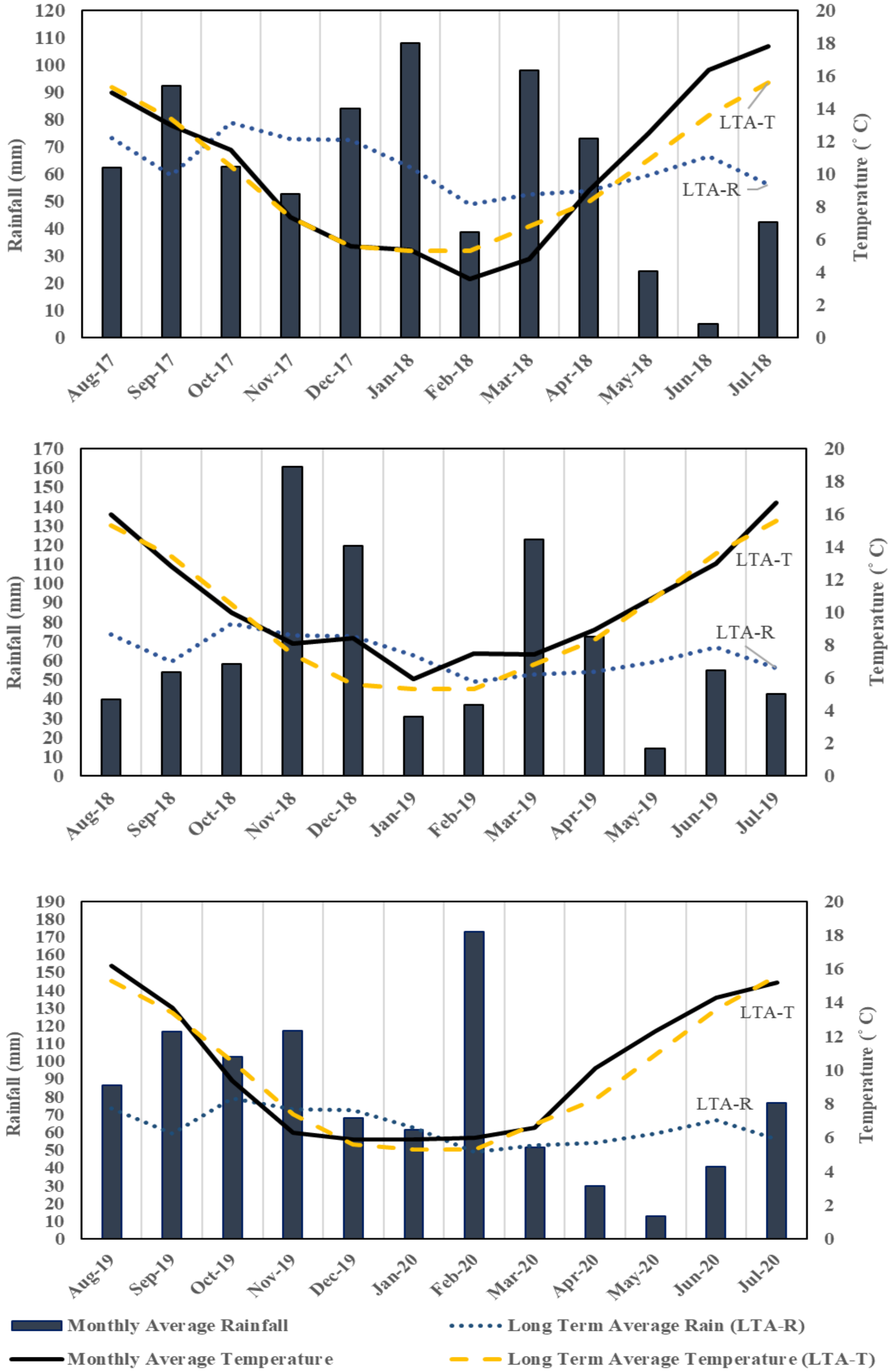


Figure 3.1. Monthly average rainfall (bar charts) and temperature (plain line) during three WOSR growing seasons (2017/18, 2018/19 and 2019/20). Dashed and dotted lines indicate 30 years of monthly average temperature and rainfall, respectively (Oak Park weather station dataset- Met Eireann, 2020)

3.4.2. Plant establishment

Plant establishment in autumn (GS 15 to GS 18) and also once at pre-harvest (GS 85 to GS 90) were within the range 21 to 35 plants/ m^2 in year 1 for all sowing dates. The range of plant establishment values in year 2 and year 3, and for different sowing dates was between 35 and 46 plants/ m^2. Sowing date did not significantly affect plant establishment.

3.4.3. Soil N Supply (SMN + crop N)

In Table 3.3., for measured spring SMN and crop N, the sum of both (SNS) are shown on zero-N plots. Sowing date had a significant effect on the measured SMN values in early spring in year 2, but ranges of SMN were small from 21.4 in SD1/ site-year 2 to 38.7 in SD2/ site-year 3. Crop N contents in February (GS 20 to GS 25) varied from 18.8 kg N/ha (SD3/ year 3) to 108 kg N/ha (SD1 / year 1). In site-year 1, crop N was reduced as SD was delayed, and in site-year 2 and 3, SD1 and SD2 had similar crop N contents, with SD3 measured to be lower. Consequently, spring SNS followed a similar trend to crop N content with a significant SD × year interaction (P-value<0.001), yet, sowing date impacted on SNS in years one and three but not in year two.

3.4.4. Harvest (final) N uptake and SNUpE on unfertilized plots

Final crop N uptake was influenced by year, SD and their interactions (Table 3.3). Sowing date affected harvest N in years one and three with the third sowing date showing less N uptake at harvest. No difference was recorded in year 2.

Table 3.3. Effect of sowing date and year-site on SMN, CropN, spring SNS, soil NUpE on zero-N plots and the related P-values

Year- Site	Sowing Dates	Mean values (kgN/ha)				
		SMN	**Crop N**	**SNS**	**Harvest N**	**SNUpE**
Year1	**SD1**	31.2	108 [a]	142[a]	125[a]	0.888 [c]
	SD2		73.5[b]	104[b]	117[ab]	1.14 [b]
	SD3		32.2[c]	63.6[c]	105[b]	1.78 [a]
SD P-value		-	<0.001	<0.001	0.017	<0.001
Mean (year 1)		31.2	71.2	102	113	1.25
Year 2	**SD1**	21.4[b]	55.2[ab]	76.6	109	1.42 [b]
	SD2	25.2[ab]	62.6[a]	87.9	97.4	1.10 [c]
	SD3	30.7[a]	36.8[b]	67.6	114	1.69 [a]
SD P-value		0.021	0.031	ns	ns	<0.001
Mean (year2)		25.7	52.0	77.0	106	1.41
Year 3	**SD1**	31.7	54.9 [a]	86.8[a]	91.7[ab]	1.06 [b]
	SD2	38.7	55.0 [a]	93.0[a]	100[a]	1.04 [b]
	SD3	30.1	18.8[b]	48.8[b]	78.0[b]	1.65 [a]
SD P-value		ns*	<0.001	<0.001	0.002	<0.001
Mean (year3)		33.0	43.0	76.3	89.4	1.29
3 site-years (SD)	**SD1**	28.9	72.9[a]	101[a]	110[a]	1.13[b]
	SD2	31.1	63.1[b]	94.2[a]	108[a]	1.14[b]
	SD3	30.1	29.4[c]	59.6[b]	98.0[b]	1.68[a]
	SD	ns	<0.001	<0.001	0.017	<0.001
	year	0.01	<0.001	<0.001	<0.001	ns
	SD×year	ns	<0.001	<0.001	0.003	ns

*ns defines non-significant

The ratio of final N uptake to spring SNS, represented as SNUpE is also summarized in Table 3.3,where SNUpE was affected by SD with significant differences recorded each year and when all three years were assessed together. The lower SNS values associated with later sowing dates resulted in greater SNUpE values, and SD3 had significantly the highest level of SNUpE each year.

3.4.5. (Apparent) Fertilizer N uptake efficiency (FNUpE%)

When considering FNUpE% a number of interactions were recorded for individual years and also across treatments. Note, CMLo was not included as one N strategy in site-year 1 (shown as: "– CMLo" for calculating the average of three years) (Table 3.4). Only in year 1 did different N strategies not result in significant changes. Yet, in terms of SD, FNUpE% was significantly different in SD1 with 40.7%, compared to SD2 and SD3 with 27.3% and 30.6% respectively. In site-year 1 also, among the SD and N strategy combinations, FNUpE was 45% with the highest value associated with CMStd and its 110 kg/ha of N application. In this year, however, low FNUpE% mainly on SD2 and SD3 were statistically similar with 27.3% and 30.6%, respectively.

In site-year 2, the addition of a lower N rate strategy (CMLo) resulted in wider variation of FNUpE% with significant values. Yet, in this year, SD2 and SD3 had higher FNUpE% when compared with the previous year, and N rates from CMLo showed higher FNUpE% on these two SDs. In SD1, high N efficiency uptake was related to CMStd with its 164 kg/ha of N insignificantly different from 81 kgN/ha of CMLo. Higher N rate strategies of CMHiY and Fixed225, with >200 kgN/ha, did not differ statistically from one another within the range of 25% to 40% in SD1 and SD2, while specifically in SD3, CMHiY with 200 kgN/ha showed about 60% of FNUpE.

Fertilizer NUpE% values in Year 3 were the highest among site-years for SD1 and SD2 with values 69.0% and 66.5%, respectively. Also, in this year, CMHiY, on SD1 and SD2 showed values of 60.3% and 72.9%, respectively, with 200 and 187 kgN/ha. Similarly, Fixed225 resulted in higher FNUpE% on the two early SDs. Moreover, CMLo provided the numerically highest efficiency of N uptake on all SDs with 56 kgN/ha, 44 kgN/ha and 118kgN/ha, on SD1, SD2, and SD3 respectively. The smallest values were related to CMHiY and Fixed225 in SD3.

The average FNUpE% across N strategies in year 2 and 3 were 53.6%, 57.3% and 48.2% respectively for SD1, SD2 and SD3. Values were higher in SD1 and SD2 from low to mid-high N rate (44 kgN/ha to 225 kgN/ha). The highest efficiency was shown in CMLo but this was only statistically significant in SD3.

Mean FNUpE% values across 3 years with just three N strategies (Fixed225, CMHiY, and CMStd) were reduced as SD was delayed, with values of 47.1%, 42.7% and 37.5% respectively on SD1, SD2 and SD3. Lowest values were observed from the three N strategies on SD3 with Fixed225, CMHiY and CMStd.

Table 3.4. Fertilizer FNUpE%, with N rates and N strategies at different years, ANOVA analysis and mean values

		Year 1		Year 2		Year3		Mean	
SD	N Strategies	N rate (kgN/ha)	↓FNUpE %	N rate (kgN/ha)	FNUpE %	N rate (kgN/ha)	FNUpE %	2yrs (+CMLoY) SD*N	3yrs (-CMLoY) SD*N
SD1	Fixed225	225	35.9^{bc}	225	24.9^{d}	225	74.3^{ab}	50.2^{cde}	44.9^{abc}
	CMHiY	170	41.1^{ab}	224	31.2^{cd}	200	60.3^{bcd}	46.1^{def}	44.4^{abcd}
	CMStd	110	45.1^{a}	164	55.0^{ab}	140	57.5^{bcde}	56.3^{bcde}	51.9^{a}
	CMLo	-	-	81	41.8^{bcd}	56	84.0^{a}	60.9^{abc}	-
Mean (SD)			40.7^{a}		38.2^{b}		69.0^{a}	53.6^{ab}	47.1^{a}
SD2	Fixed225	225	25.7^{d}	225	36.5^{cd}	225	54.7^{cde}	45.8^{def}	38.3^{cd}
	CMHiY	225	30.8^{cd}	205	40.1^{bcd}	187	72.9^{abc}	59.1^{abcd}	47.8^{ab}
	CMStd	165	25.5^{d}	145	41.9^{bcd}	127	63.2^{bcd}	54.3^{bcde}	42.6^{bcd}
	CMLo	-	-	61	65.1^{a}	44	75.1^{ab}	70.2^{a}	-
Mean (SD)			27.3^{b}		46.9^{a}		66.5^{a}	57.3^{a}	42.7^{b}
SD3	Fixed225	225	37.3^{abc}	225	31.4^{cd}	225	39.5^{ef}	35.5^{f}	36.3^{d}
	CMHiY	260	29.9^{cd}	200	59.7^{ab}	261	29.5^{f}	42.2^{ef}	36.9^{cd}
	CMStd	200	24.7^{d}	140	48.0^{abc}	201	49.3^{de}	48.7^{cdef}	39.3^{bcd}
	CMLo	-	-	57	56.9^{ab}	118	67.4^{abcd}	66.1^{ab}	-
Mean (SD)			30.6^{b}		48.0^{a}		46.4^{b}	48.2^{b}	37.5^{c}

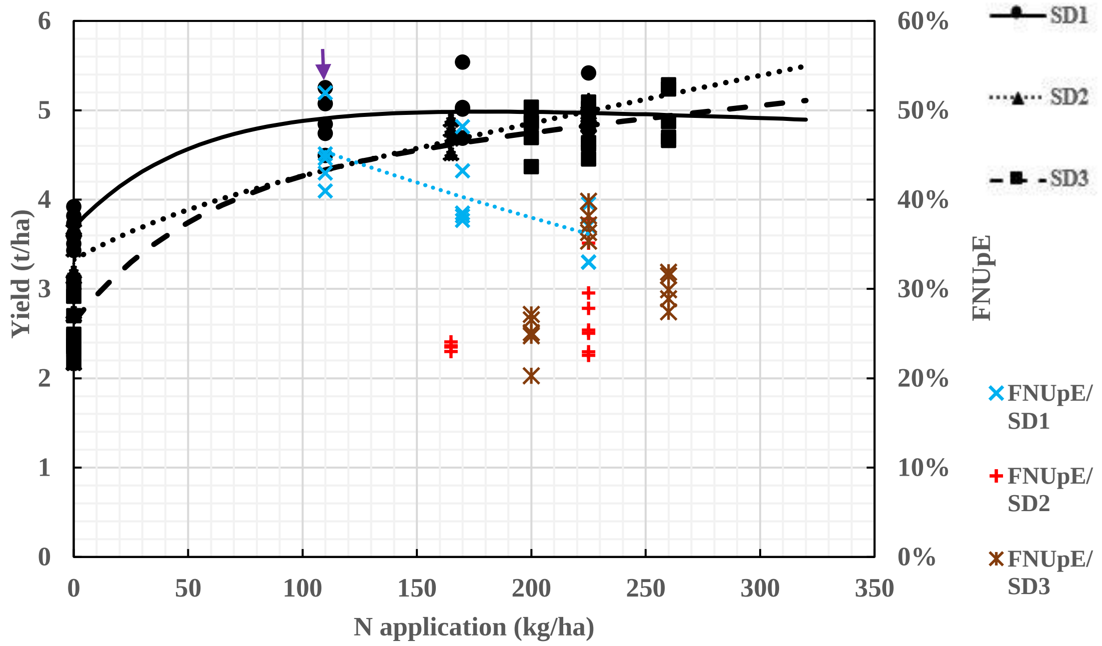
	P-value year 1	P-value year 2	P-value year 3	P-value year 2, year3 (+CMLoY)	P-value 3 years (-CMLoY)
SD	<0.001	<0.001	<0.001	<0.001	<0.001
N strategy	ns	<0.001	<0.001	<0.001	0.002
Year	-	-	-	<0.001	<0.001
SD×N	<0.001	<0.001	<0.001	0.009	0.007
SD×year	-	-	-	<0.001	<0.001
N×year	-	-	-	<0.001	<0.001
SD×N×year	-	-	-	<0.001	<0.001

Different letters indicate significant differences at P= 0.05 within a factor and parameter, and are based on three-way significant interaction
↓FNUPE% mean analysis of site-year 1 when SD×N were significantly different

3.4.6. Optimum N rates in relation with FNUpE% and yield

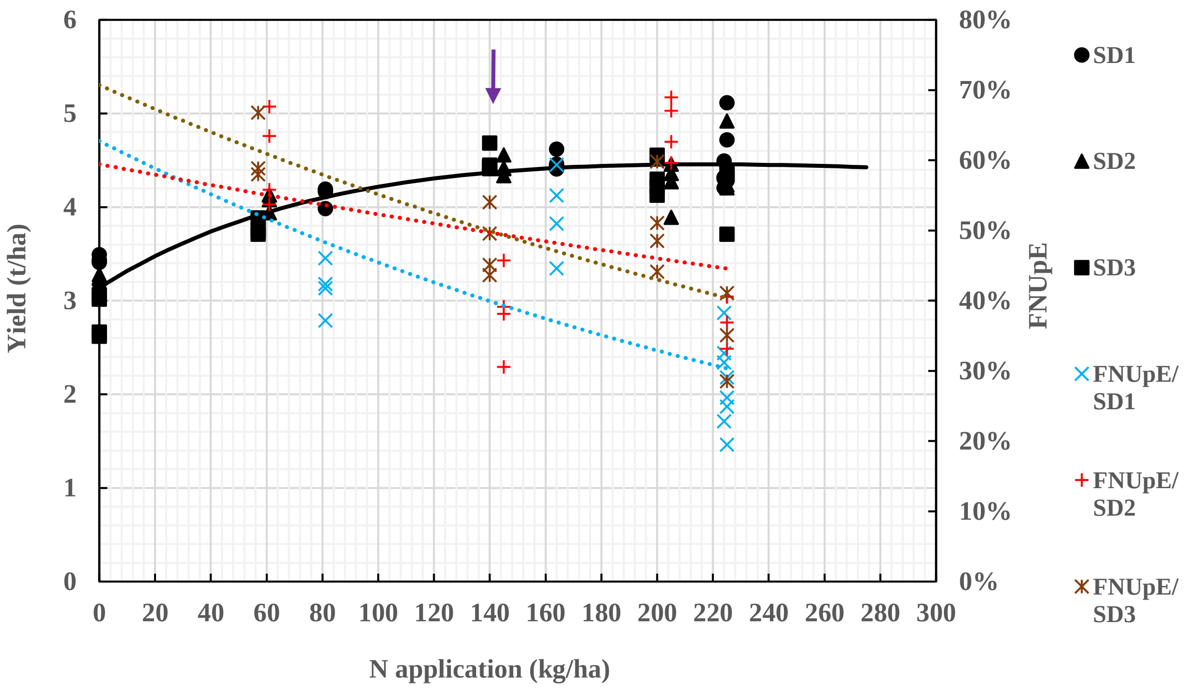
To detect the optimum N rate (Nopt), yield (on y-axis) and N rates were regressed (Figure 3.2 - A to C) for individual years, separated by theirs SDs and parameters represented in Table 3.5. Nitrogen rates and FNUpE% (on the secondary y-axis) were regressed similarly (Figure 3.2 - A to C). This was to define the closest FNUpE% to the Nopt points while considering yield values. This approach differentiated the supra-optimal values, or defined how FNUpE% was far from 60% of UK- CM. Based on the parameters in Table 3.5, Nopt in site-year 1 was 113 kgN/ha, which was the closest N strategy to the 110 kgN/ha, predicted as CMStd. For the first two years, the adoption of CMStd was the best option to Nopt with FNUpE values from 42% to 55%. In year 3, for which FNUpE values were generally higher in SD1 and SD2 with 60.3% and 72.9% (Table 3.4), Nopt of 190 kgN/ha was the selected N strategy. For SD3 in this year, CMStd with 49.3% and 201 kgN/ha was chosen as the possible economical rate where fertilizer N rate was mostly efficient. The detail of this study is collected in Table 3.6.

A



6
5
4
3
2
1
0
Yield (t/ha)
60%
50%
40%
30%
20%
10%
0%
FNUpE
0
50
100
150
200
250
300
350
N application (kg/ha)
SD1
SD2
SD3
FNUpE/ SD1
FNUpE/ SD2
FNUpE/ SD3

B



6
5
4
3
2
1
0
Yield (t/ha)
80%
70%
60%
50%
40%
30%
20%
10%
0%
FNUpE
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
N application (kg/ha)
SD1
SD2
SD3
FNUpE/ SD1
FNUpE/ SD2
FNUpE/ SD3

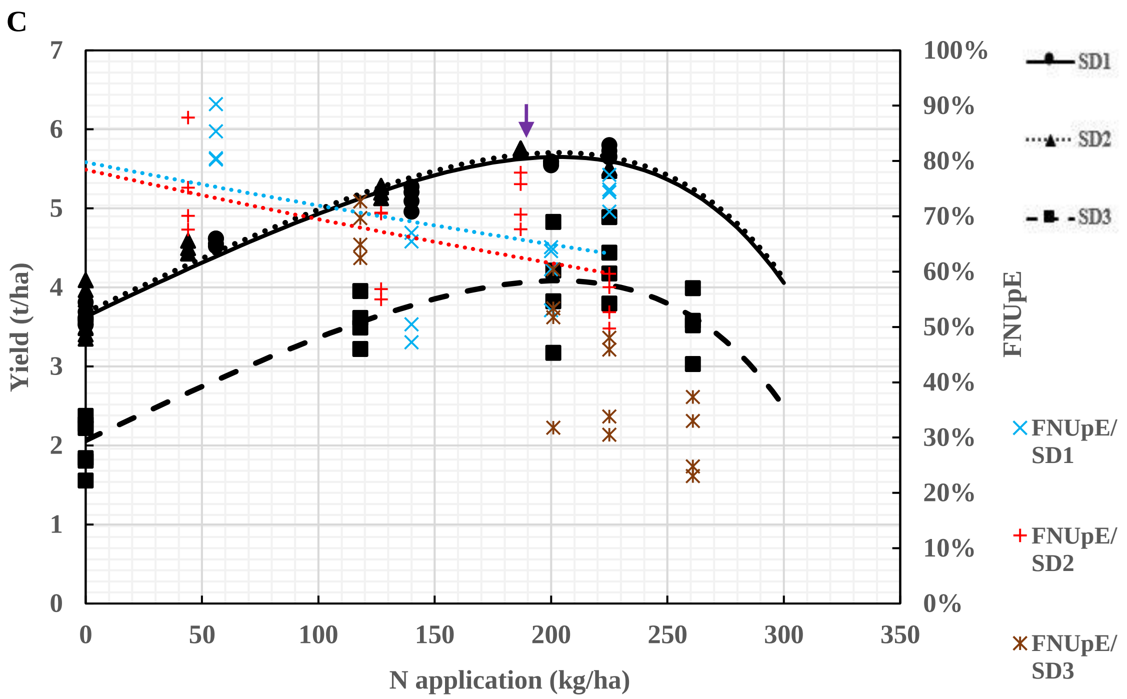


Figure 3.2. (A to C): Fitted linear plus exponential curves on year 1 (A), year 2 (B) and year3 (C) with their SD1, SD2 and SD3; FNUpE% at secondary y-axis shown as cross, plus and star respectively on SD1, SD2 and SD3 for each year. All points represent each replication. Purple arrow shows the optimum N rate. The dotted colourful trend lines are the possibly defined exponential relationship between FNUpE and N rates corresponded to same colour of FNUpE for each SD.

Table 3.5. Linear + expo parameters ($Y= A+ BR^N+ CN$), S.E. is the standard error of the observation with degrees of freedom shown as (d.f.), Optimum N rate (Nopt),and maximum yield at Nopt, proportion accounted for variance (adjusted R^2), and the P-value of the stepwise regressed function.

Site-year	SD	Curve parameter				S.E. (d.f.)	Nopt (kg/ha)	Yield Max (t/ha)	adj. R^2	*P-value*
		A	B	C	R					
	1	5.21	-1.52	-0.00098			113	4.91	0.91	<0.001
Site-year 1	2	3.81	-0.48	0.0052	0.981	0.025 (114)	undefined			
	3	4.23	-1.61	0.0027			undefined			
Site-year2		5.1	-1.96	-0.0020	0.989	0.253 (56)	143	4.37	0.77	<0.001
	1	3.69						5.63		
site-year3	2	3.75	-0.065	0.014	1.01	0.288 (67)	190	5.69	0.93	<0.001
	3	2.12						4.06		
	1	6.68	-3.03	-0.0046			157	4.93		
Across years	2	7.57	-4.17	-0.0079	0.993	0.465 (197)	148	4.90	0.74	<0.05
	3	6.70	-4.23	-0.0062			175	4.34		

Table 3.6. Selected FNUpE% closest to Nopt to define the best N strategy, N rates, and SDs for each separated year and SD

			Closest		
Site-year	**Sowing Date**	**Nopt (kg/ha)**	**N strategy**	**related N rate (kg/ha)**	**FNUpE%**
Year 1	**SD1**	113	CMStd	110	45.1%
Year2	**SD1**	143	CMStd	164	55%
	SD2		CMStd	145	41.9%
	SD3		CMStd	140	48.0%
Year3	**SD1**	190	CMHiY	200	60.3%
	SD2		CMHiY	187	72.9%
	SD3		CMStd	201	49.3%

3.5. Discussion

In this study, which was conducted in a climate with frequent mild winters, post winter SMN ranged from 21.4 to 38.7 kgN/ha in two years measurement, separated by SDs. When considering crop N at specific sowing dates and years, values differed from 18.8 to 108 kgN/ha. Therefore, spring SNS ranged significantly from 49 to 142 kgN/ha across SD and year combinations. Final crop N uptake at harvest was slightly more than spring SNS in SD1 and SD2 and this resulted in (>1) SNUpE values of 1.13 and 1.14 across three site-years on SD1 and SD2. Hence, there was a modest amount of additional soil N (13 to 14 kg N/ha higher than the measured SNS) in the earlier SD. Final N uptake on SD3 was the greatest value in site-year 2 by 114 kgN/ha, and least in site-year 3 at 78 kgN/ha. Soil NUpE ratios were similarly high statistically, and ranged from 1.65 in site-year 3 to 1.78 in site-year 1. The latest SD, therefore, had significantly the highest SNUpE ratio of 1.68 across SDs. The considerably higher SNUpE results on SD3 were due to mainly low SNS values presenting as the denominator in the equation. Also, there was a greater N uptake of 38.6 kgN/ha for SD3 compared to 11.4 kg N/ha for the mean values of extra N for SD1 and SD2. This indicates a greater scavenging capacity of the less advanced plants from spring to harvest time due to fallen-behind growth stage. Small crop N content measured in early spring had less leaf drop during stem extension onwards which was another possible reason for higher SNUpE on SD3.

In a UK study by Kindred *et al.* (2012) a wider range of SMN, from 30 to 60 kgN/ha was observed, with crop N ranging from 29 to 55 kgN/ha. However, the lower crop N values were associated with the higher SMN, yet, no difference was shown between spring measured SNS and final N uptake in the UK study. Hence, SNUpE was counted as 100% on most site-years. It was concluded that “WOSR is efficient at remobilizing N from dying leaves and little N was lost from dropped leaves” (Kindred *et al.*, 2012). In another UK study by Berry and Spink (2009), SNUpE was measured as 100% of uptake efficiency when regressing early spring SNS (as explanatory variable) and final N harvest (as responsive variate) where the slope of the linear function was 1.07, and R^2 explaining the variables was 0.76. It was reported as a quite satisfactory relationship in conditions where "no systematic difference was noticed between sites and seasons"; however, one variety (Castille) showed on average a higher ratio of final N uptake to spring SNS of up to 1.30. The authors explained that values of > 1 SNUpE were related to sampling time or higher N mineralization after spring. Both UK studies concluded that SMN and crop N are equally important to predict crop`s final N uptake on unfertilized plots, and for the reason of simplicity SNUpE should be considered as 1 (=100%). In the research reported here, spring SMN ranges were smaller and crop N uptake higher than the UK studies. It is tempting to assume that low SMN in the current study made this value less reliable to consider in early spring for calculating SNS. Perhaps a high volume of mineralized N cannot be available to the plant as the result of run-off loss, leaching, immobilization, or denitrification. This was well-supported by SD3 SNUpE, where higher AAN was taken up and the synchronization between plant N demand and N availability was better adjusted, as this conception was studied before (Robertson and Vitousek, 2009). It is therefore only possible to debate comparatively that spring SNS on earlier SDs more accurately predicted final N uptake, whereas this was not the case on SD3. Hence, this implies in such a climate, earlier sowing dates are preferable making SNS calculation a more reliable trait. Moreover, it is important to consider the value of SOM % and also the soil texture of loam in this study. Respectively, SOM values were 4.4%, 5.3%, and 4.6% for site-year 1, 2 and 3. These values were considerably higher than the 2 to 3% of UK croplands SOM based on (Verheijen, *et al*., 2005).

The maximum amount of AAN release in UK studies was reported to be about 40 kgN/ha measured on low spring SMN according to Kindred *et al*., (2012). In another UK study by Blake-Kalff and Blake (2014) the AAN was measured, using anaerobic incubation tests during growing season after spring. They reported an average AAN of up to 60 kgN/ha as the potential mineralized N release. Authors concluded that AAN quantity depends on soil organic matter, C:N ratio and soil textures which influences soil temperature and moisture retention.

Studies from different climate ranges (Germany, France, Netherlands, Denmark) and Atlantic-continental climate (UK) on N supply to WOSR have shown that considering spring SNS (mainly focused on SMN), is good but not “satisfactory” (Łukowiak and Grzebisz, 2020), because the “black box” in the fertilizer N decision is related to the unknown soil resources and their availability during the growing season (Grzebisz *et al.*, 2018).

In the continental-Alpine climates of Germany and France, soil mineralization dynamics vary hugely during autumn and winter as mineralization in early spring depends on regional rainfall and temperature (Sieling, 2000), hence no specific or general SNUpE amount has been reported in those areas. Consequently, different prediction systems are used; Henke *et al.* (2009) concluded that autumn canopy N + SMN is a better indicator for adjusting N fertilizer rates compared to spring canopy N+SMN. This is because soil N availability in spring is lower due to low soil temperature, little mineralization over winter, and nitrate leaching (Sieling *et al.*, 1999). Conversely, the potential of WOSR to take up N during autumn was reported to be above 100 kgN/ha (Reau *et al.*, 1994; Sieling, 2000).

The ability to measure SNS and have an estimation of AAN on a site and year basis are the most immediate factors for improving FNUpE (Dawson *et al.*, 2008). The measured FNUpE% in this study varied hugely, ranging from 24.7% to 84% across all site-years- SD and N strategies. Site-year values differed with FNUpE%, increasing progressively from year 1 through to 3. The addition of CMLo in year 2 and 3 improved FNUpE, as it included lower N application rates. In year 1, SD2 and SD3 had the narrower range of N rate, with no medium N application rate less than 165 kgN/ha. Moreover, this situation coupled with the dry harvest time impacting on N uptake, meant that the curve fitting did not allow the Nopt to be defined for SD2 and SD3 in this year. Dry conditions from May up to harvest time (2018) contributed to a reduction in N uptake (notable in SD1 with < 1 SNUpE) and poorer fertilizer efficiencies in that year. In year 2, the earlier sowing date crops were impacted by the 2018 dry autumn led to lower SNS ranges than site-year 1 with wider N application rates. Also, in year 2, yield was comparatively lower (4.4 t/ha max yield) and consequently Nopt was calculated as a smaller value (143 kgN/ha), comparing to the Nopt of site-year 3.

In year 3 there was a much greater disparity in FNUpE% across the sowing dates with SD1 and SD2 having mean FNUPE values of more than 65% and a drop to 46% for SD3. Crops sown in SD1 and SD2 had a high yield (maximum yield was 5.6 and 5.7 t/ha respectively) and an optimum N application of 190 kg/ha resulting in less risk of super optimal application with many of the N strategies. The latest SD had a much lower yield potential, yet higher vegetation. Based on observations, late sown crops were thicker, but were shorter with late-flowering timing. It is hypothesized that fertilizer N was not an available N source for these crops the way soil N deposition was. Perhaps, the varied temporal-spatial situation did not allow a synchronization between crop N demand and fertilizer N uptake. Fertilizer NUpE% varies based on growth stage of the crop: early application of N has been reported to be more efficiently taken up by early sown crops as the rapidly developing plants move to stem elongation where nitrate uptake increases (Malagoli *et al.*, 2004). In a study by Sieling *et al.* (2017) conducted in north Germany, the date of plant establishment also affected FNUPE%: early sown plots (1st and 3rd week of Aug) had higher FNUPE% than late sown ones (1st and 3rd week of Sept). Authors also showed FNUPE% reduced substantially from 46% to 28% with N application rates rising from 80 kgN/ha to 280 kgN/ha.

In UK literature, the FNUpE% also varied across site-years with ranges from 23% to 63%. At 100 kgN/ha, FNUpE% was 67%, whereas at 240 kgN/ha the value reduced to 43% (Berry and Spink, 2009). However, no published studies have been reported on different SDs in the UK, although delayed sowing date led to no significant yield penalty in two site-years out of four experiments, despite the fact that seed rate was higher (60 to 120 seeds/m^2) in that study (Lunn *et al.*, 2001).

In this study, there was only a slight difference between spring SNS and final N uptake on early SD (End Aug). Therefore, in case of early sowing UK-CM is adaptable to Irish climate while considering the FNUpE% is lower on earlier SDs. Late sowing dates (perhaps 20th September) should be avoided, as there would be an under-estimation of spring SNS measurement on final N uptake, so that more AAN would be evident during the growing season. Also, fertilizer N uptake will be least efficient at a later sowing dates due to wet soil and weather conditions, leaching loss, immobilization, denitrification and run-off depending on site-year situation.

Measurements such as SMN, crop N and possibly N deposition (AAN) would help mitigate the risk of imprecise prediction in this climate, particularly on SD3.

Winter OSR N management in continental Europe uses autumn crop N and SMN, and the possibility of leaf loss turn overs has been estimated as a coefficient in N requirement models (Dejoux *et al.*, 2000).

3.6. Conclusion

Soil NUpE on late sowing dates was greater than 100% in the Atlantic milder climate of this study. This implies there were higher values of final N uptake than the measured spring SNS on zero-N plots, hence, an additional available N to the crop has become released to the system for the crops to take up during growing season. Highest SNUpE was related to the latest SD of mid-Sept with averagely 1.68, whereas SD1 and SD2 were only slightly different for 100% of soil NUpE assumption with 1.13 and 1.14, respectively, on average across years. Also there were various FNUpE% differed under the influence of SD, site-year, and N strategies. Fertilizer NUpE% was studied through the regression analysis with yield and N rates to present it as closely as possible to Nopt. In spite of lower FNUpE% than the assumed UK standard of 60%, maximum obtained yield was considerably higher than 3.5 t/ha of UK-CM.

Having an approximate knowledge of AAN of the site-year, alongside spring SMN and crop N would result in greater precision of fertilizer N prediction on late sowing dates, because soil N uptake was highly efficient on these crops, but FNUpE was smaller (48.6%). The AAN was calculated as 38.4 kgN/ha on late SDs, whereas this was 10 and 12 kgN/ha on SD1 and SD2 across years.

A slight difference of SNUpE from 100% efficiency and FNUpE of 55% on early SDs suggested that spring SNS is a better indicator for predicting final N uptake in comparison with late sown crops.

4.0. Nitrogen uptake to optimize canopy size and light interception for high yielding winter oilseed rape (*Brassica napus* L.) grown in a mild Atlantic climate

4.1. Abstract

Crop N demand means the amount of N that the crop needs to take up for the formation of an optimum canopy size, which is measured using green area index (GAI). Optimum GAI is decided based on the maximum amount of the fractional interception (FI) beneath the crop, also at maximum produced yield within the economical optimum N application. This study has been set on different canopy sizes using various N strategies of Fixed225, CMStd, CMHiY, IrishCM, CMLo, and Zero N (as subplots) within three sowing dates (SD1, SD2, and SD3) (as main plots). Four replications were conducted for each N strategy within each SD during three years (2018 to 2020). Multiple linear and non-linear regressions were run on GAI and crop N content, GAI and FI, GAI and yield using a regression method (through calculating the reduced sum of square error) grouping by different variables to define the best-fitted parameters. Results demonstrated that from early growing stage (GS) of pre-stemming up to the post flowering GS, the crop N uptake for each unit of GAI formation was 54.1kgN/ha (±2.92 Std. error of the mean). The optimum GAI for intercepting 95% of FI, across all SDs, on average of three years was 4.00, although there appeared to be a wide range of 0.95 confidence interval (CI) for SD3 in site-year3. Most variations were related to site-year 3, with a significantly smaller extinction coefficient of 0.670 due to a higher number of younger leaves (erected shape) for this specific late-sown site-year, with upper GAI 95% CI limits of 4.50. Results, therefore, demonstrated that GAI had a slightly wider range if sown at a later timing (after 17th September). GAI and yield regression showed that maximum GAI at economic yield, on an average scale of three years, for SD1 and SD2 were 3.08 to 4.67 GAI measured as lower and upper limits of 0.95 confidence interval, whereas, for SD3 values were 3.86 to 4.79. Moreover, no difference was

found between optimum GAI values and yield for N treatments of Fixed225, CMHiY and CMStd; hence, N application could be reduced by adopting CMStd which is 60kgN/ha saving over CMHiY.

4.2. Introduction

Although the application of N fertilizer in spring almost doubles the seed yield of WOSR (Sylvester-Bradley *et al.*, 2015), finding an economical and environmentally benign N rate is necessary to provide a balance between crop N demand and N supply. For this purpose the aims of this study are to: a) reduce N surpluses (supra-optimal N applications) thereby reducing nitrate leaching, run-off and volatile nitrous oxide or ammonia emissions from agricultural production (Billen *et al.*, 2013) and; b) avoid sub-optimal N supply which may affect harvest seed yield.

To achieve greater precision in optimum N rate determination, the amount of N that the plant needs (crop N demand), the supply of available N from soil (soil N supply, SNS), and the apparent fertilizer N uptake efficiency by the crop (fertilizer N recovery) are factors to consider in individual situations (Appel, 1994; Sylvester-Bradley *et al.*, 2010). These three components may all vary in different situations.

Ireland`s Atlantic maritime climate is characterized by a mild seasonal change, due to its geographic latitude. The average meteorological values in winter on the east side of the country have been 9.8˚C temperature, 10˚C soil temperature (20 cm), 758 mm rainfall with average daily sunshine hours of 3.9 h (1981-2010 data, Met Eireann, 2019).

Teagasc major and micro nutrient advice for productive agricultural crops by Wall and Plunkett, (2016) outlined the maximum N application limits allowed by the EU Nitrates Directive. The advice is mainly based on previous cropping history only, with no consideration of crop N demand on a site-year basis. Variation in autumn and winter weather can result in poor crop establishment, which would mean that an excess spring N application would be an inappropriate response from growers. This could result in N losses through environmental risk pathways.

Among the factors to be considered for optimum N determination, crop N demand has more scope for management intervention by breeding and/or agronomy approaches (Sylvester-Bradley *et al.*, 2010). Also, the formation of yield as a function of canopy structure, light distribution, pod and seed retention of WOSR in the UK climate has been studied (Lunn *et al.*, 2001). In a situation with smaller leaf loss over winter and therefore a larger canopy build-up, a reduction of N application in the following spring was suggested in 1980s, with no yield penalties recorded in the UK (Mendham *et al.*, 1981a). Similar studies in a continental European climate (i.e. Germany) by Henke *et al.* (2009) concluded that even if canopy N is lost due to winter frost, the optimum N requirement is decreased with increasing canopy N present in late autumn. Hence, the effect of season and/or regional climate influences dry matter accumulation, N uptake, GAI formation, and subsequently fertilizer N requirement.

By definition, GAI is the one-side of the total horizontal crops "green areas per unit of ground" (Chen and Black, 1992). Values for GAI depend on several factors such as plant population, water and N supply and can be between 0.5 to 2.0 at stem elongation, and between 2.0 and 7.0 by flowering (Kirkegaard *et al.*, 2021).

The initial step in identifying relationships between N fertilizer requirement and yield is to prioritize the traits associated with crop N responses. These traits were set out as a stepwise system in Sylvester-Bradley and Kindred (2009) study on wheat crops. The system describes the required N uptake for GAI formation; GAI for light interception; light interception to assimilate photosynthates and biomass accumulation, and finally biomass accumulation for yield formation. Yield itself is limited by genetic traits and N use efficiency (NUE). With WOSR, this stepwise relationship, however, may not be as straightforward (Lunn *et al.*, 2001). The possibility of producing an excessively dense crop as the result of overestimating N fertilizer requirement, or using an early sowing date, would mean poor radiation interception beneath the flower canopy, lodging and yield reduction. However, results from a number of studies

(Jenkins and Leitch, 1986; McWilliam *et al.*, 1995; Mendham *et al.*, 1981a; Spink *et al.*, 2002; Stafford, 1996) show that a sparser pod canopy can produce comparable or significantly better yield values than a denser canopy under the same conditions of incident radiation.

A system of N prediction known as “canopy management (CM)” was developed from UK studies (Berry *et al.*, 2011; Berry and Spink, 2006; Sylvester-Bradley *et al.*, 1998) and forms part of the N recommendation system in the AHDB Nutrient Management Guide (RB209) (www.AHDB.org.uk). The N fertilizer and soil mineral N uptake efficiency characteristics of this system were assessed in Chapter 3. Previous research showed that in the UK maritime-continental climate, there was a close relationship between N uptake and GAI formation (Stokes *et al.*, 1998). The optimum canopy size at flowering (BBCH, GS 65), for light interception and seed yield, was measured to be between 3 and 4 units of GAI (Lunn *et al.*, 2003b) which supported by earlier work by Mendham *et al*. (1981). Based on their studies, the GAI of 3 to 4 is enough to intercept 90 to 95% of solar radiation, but as the plant develops to flowering stage, leaves are shaded by the flowering canopy, then later by pods resulting in little light penetration for larger canopies. To have a single canopy size value for simplicity, on average the optimum size at flowering was considered as 3.5 unit of GAI (Lunn *et al.*, 2001). Based on the assumption that each unit of GAI contains 50 kgN/ha, the crop N demand by flowering for the optimum size of the canopy was calculated as 175 kgN/ha (=3.5×50) using UK-CM principles (Berry *et al.*, 2011; Berry and Spink, 2009a; Lunn *et al.*, 2001).

The relationship between the fraction of light interception and GAI follows an exponential curve functioning as described in Monteith (1965) and also confirmed for WOSR in UK conditions by Lunn *et al.* (2001) . A crop with a k value of 0.70 is expected to intercept 0.5 of the radiation with GAI=1, 0.75 with GAI=2 and 0.9 with GAI=3 according to Lunn *et al.* (2001)- Figure 4.1. The relationship between the fraction of light interception (FI) and GAI is given as:

$FI = 1 - e^{-k \times GAI}$

Where “k” is the extinction coefficient, which is a higher value than with cereals as Brassicas` leaves are more prostrate. Winter OSR *k* values are measured to be 0.60 to 0.75 (Gabrielle *et al.*, 1998; Justes *et al.*, 2000; Mendham and Salisbury, 1995; Mendham *et al.*, 1981b).

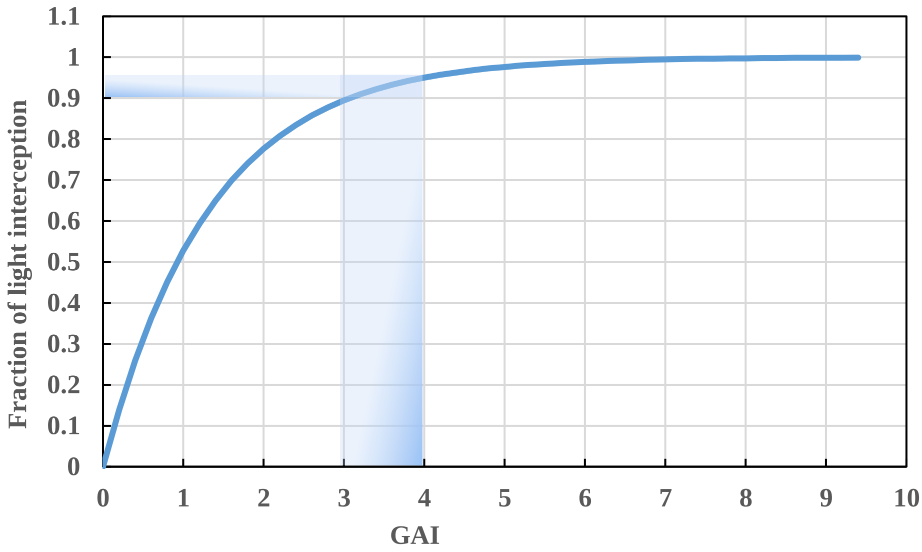


Figure 4.1. Regression between FI and GAI for intercepting 0.90 to 0.95 ratio of FI within optimum range of 3 to 4 unit of GAI (Redrawn from ADAS Rosemaund, 1996)

In many studies, such as Takashima *et al.* (2013), WOSR yield is dependent on rainfall, temperature, and radiation from sowing date to flowering, and from flowering to maturity. The applicability of the UK- CM system in a climate with a milder overwinter period than where the system originated has not been evaluated. Also, to-date no studies have reported any data focusing on potential optimum GAI values to intercept maximum FI and also yield production at flowering in WOSR. Therefore, this research firstly tests the crop N demand; then the optimum GAI at flowering based on 95% of FI and maximum economical yield within their 0.95 confidence interval (CI). The aims are to determine: 1) the required N uptake for building up each unit of canopy size (GAI), and 2) the optimum canopy size for light interception and yield formation at flowering stage in a mild Atlantic climate.

4.3. Materials and methods

4.3.1. Field experiment

Three experiments were carried out on different sites at Oak Park crop research centre (52°51′ N, 06°54′ W, 62 m a.s.l.) in 2017-18 (year1), 2018-19 (year2) and 2019-20 (year 3). The main plot treatments consisted of different sowing dates: mid Aug (SD1), End Aug (SD2), mid-Sep (SD3) and were allocated randomly within each block in a randomized block design with four replications. Within each sowing date, sub-plots of different N rate levels including: UK-CM N strategy and variants of a 'Fixed' rate 225 kgN/ha based on a general recommendation and unfertilized (Zero-N) plots as described in chapter 3 are briefly repeated in Table 4.1.

A subtraction of an estimated final N uptake of plant components in site-year 1 and site-year 2 from spring soil N supply led to the development of a new CM in year 3, named IrishCM (Described in Appendix1). This CM was estimated to have an extra 50 kg/ha of N release between spring and harvest time and therefore it was calculated as equation (Eq. 4.1) below

$$\text{Irish CM} = \frac{\text{Crop N demand} - (\text{SNS} + 50)}{\text{fertilizer N recovery \%}} \qquad \text{(Eq.4.1)}$$

The WOSR variety, Anastasia, was sown at a seed rate of 50 seeds/m^2 , the preceding crop was winter barley and all sites were classified as grey-brown podzolic soil (Creamer *et al.*, 2014) of loam texture. Calcium ammonium nitrate (CAN, 27%) was used as N fertilizer, and all other crop inputs were applied according to then current advice from the Teagasc crop report (2019) to prevent the risk of yield limitation due to nutrition, disease or pests.

Table 4.1. Nitrogen strategies at different SDs and years

	Sowing Date (SD)	N strategies (KgN/ha)					
		Fixed225	**CMHiY**	**CMStd**	**IrishCM**	**CMLo**	**Zero N**
Year 1	**SD1**	225	170	110	-	-	0
	SD2	225	225	165	-	-	0
	SD3	225	260	200	-	-	0
Year 2	**SD1**	225	224	164	-	81	0
	SD2	225	205	145	-	61	0
	SD3	225	200	140	-	57	0
Year 3	**SD1**	225	200	140	116	56	0
	SD2	225	187	127	104	44	0
	SD3	225	261	201	178	118	0

4.3.2. Measurements

4.3.2.1. Biomass, N concentration, and yield

As described in Table 4.2, the measurements of biomass dry matter (t/ha), GAI and N content (kg/ha) were conducted at a number of different growth stages. For biomass and GAI determination, two 0.5 m^2 samples were taken from each individual plot and a weighed sub-sample of 20% represented plant components such as leaves, stems, flower buds, and hetero-trophic pods. Then, a leaf scanner (Delta-T) was set for passing green plant components to measure their areas for GAI calculation. The separated plant components were oven-dried (72 h, 75˚C) for the final calculation of biomass as the summation of all plants fractions (t/ha). Following drying, different plant parts were ground and the moisture content was measured separately prior to N analysis using the Dumas method (Rapid N Cube, Elementar Analysen-systeme, Hanau, Germany). Crop N was finally presented in kg/ha using the dry weights (t/ha) of components and their N concentration. Final combine yield was measured using a Deutz Fahr 37.1 plot combine with Zuern Oilseed rape header and Harvestmaster™ weighing equip-ment.

4.3.2.2 Sunscan measurement at flowering

Incident and transmitted radiation was measured at flowering (~ GS 65) using a Sunscan Canopy Analysis System (Delta-T Devices, Cambridge- UK) which was set as "SS1-Com-R4 complete system" with its radio link (delta-t.co.uk). The aforementioned system consists of a scanning probe with a 1 m length and 64 photodiodes. A combination of the video wireless linked to a Beam Fraction Sensor (BFS) as a sunshine sensor was used. The complete system is used for a higher accuracy in changing weather conditions, and controlling the probe func-tionality. In this study, direct solar beam (not diffuse) was used as the source of data to calculate the fraction of light interception of the photosynthetic active radiation (PAR) based on Campbell, (1986). The probe was placed under the canopy, roughly 20 to 25 cm above ground including 95% of the crop height, with repeated readings at 8 different positions in the plot. To reduce the error of reading, the device was used at no-rain and uniform overhead conditions. The average Sunscan™ measured fraction of transmitted light divided by the measured incident light (as a ratio) was reduced from 1 to achieve the FI.

To determine N uptake per unit of GAI, a wider range dataset across seasons and at various GS were used, but on limited treatments (only on zero-N and Fixed225 treatments). Hence GS was categorized in three groups as i) pre-stem elongation, ii) stem elongation and flowering and iii) post flowering measurement for that specific linear regression analysis.

Table 4.2. The measurements and their correspondent growth stage (BBCH)

Measurements	GS	Grouped GS for the analysis
Biomass/ GAI/ N content	Rosette leaves (GS- 13 to 19)	Pre-Stem
Biomass/ GAI/ N content	before stem elongation (20 to 29)	
Biomass/ GAI/ N content	Stem elongation, flower buds visible stage (GS- 30 to 58)	Stem elongation to flowering
Biomass/ GAI/Intercepted radiation/ N content	flowering, heterotrophic pod appearance (59 to 69)	
Biomass/ GAI / N content	Pod development and Seed present (GS- 71 to 81)	Post flowering

4.3.3. Calculations and statistical analysis

Multiple linear regression analyses using a stepwise method were performed to generate the best-fit relationships for the measured variables using Genstat 19.1 (www.vsni.co.uk). Linear models were used for GAI (as a responsive variant) and crop N (as explanatory), and non-linear models between the FI and GAI and also yield and GAI at flowering. Each stepwise regression had four steps with similar procedure as defined in Chapter 3, where 1) a common best fitted line for different variants (SDs and GS) across year can vary 2) parallel best-fitted lines allowing the constant (intercept) to vary, 3) non-parallel best-fitted lines by allowing slopes to vary and 4) separated curves for each variant can produce different parameters to vary. The calculated error sum of squares from steps 1 to 4 and the variance ratio tested the improvement in fit over the previous model. If there was no significant improvement between two stages, then the previous model was used as the best description of the data.

A paired t-test comparison was used for slope and intercept with their equal variance to determine whether each unit of GAI differs at various source of variants (SDs across years, all GS and SDs at flowering).

4.3.3.1. Calculating fractional interception (FI)

Transmission of beam radiation, I(t), by vegetation has generally been described using an equation followed Beer-Lambert`s law, where I(0) is the flux density of beam radiation on a horizontal surface above the canopy. Then I(t) is the flux density below the GAI, and k is the extinction coefficient for the canopy (Eq. 4.2).

$I_{(t)} = I_{(0)} \exp^{(-kGAI)}$ (Eq. 4.2)

The extinction coefficient represents the area of shadow cast on a horizontal surface by the canopy divided by the area of leaves in the canopy (Monteith, 1975) or the average projection of leaves on to a horizontal surface. Equation 4.3. was substituted as a non-linear model between FI and GAI as the model for calculating the parameters.

$FI = 1 - e^{-k \times GAI}$ (Eq. 4.3.)

Fractional interception (FI) is $\frac{I(t)}{I(0)}$, “e” is Napier`s constant (=2.718) and “k” describes the architecture of the canopy layers and differs as the crop develops.

Optimum GAI was defined at 95% of the FI with its 0.95 lower and upper limits of confidence interval (CI) were investigated.

In addition Linear + exponential (lin+expo) models were best fitted to regress GAI in response to yield grouped by SD and year(s) using a function derived by Lunn *et al.* (2001) (Eq. 4.4).

$Y = A + BR^{GAI} + C \times GAI$ (Eq. 4.4.)

Where Y is the yield, A, B, C and R are constant parameters which respectively define: the asymptote; the effect of omitting GAI; the slope of the asymptote; and the curvature of the response (Sylvester-Bradley, 1992). Based on a UK assumption, the economically optimum GAI points are at 95% of maximum yield within their 95% of CI (Sylvester-Bradley *et al.*, 2002).

4.4. Results

4.4.1. N content to form GAI at different site-years, SDs, and GS

The t-stat comparison (P-value<0.05) of slopes and the intercepts of the equations were compared on the three different SDs to test for significance. Intercepts (named in the table as constant or b) values (Table 4.3), were discarded from the equation. The slope values were used to calculate crop N content per GAI unit as physiologically it is not feasible to consider intercepts.

4.4.1.1. Crop N content and GAI at different site-years

Crop N content and GAI were regressed and grouped at different SDs for each year. The 3rd SD differed significantly from the other sowing dates (Figure 4.2-A). Crop N content per GAI unit for values across years and growth stages at different SDs were respectively 57.4, 57.8, and 47.3 kgN/ha. Table 4.3 also shows the crop N content values per 4 units of GAI as a standard GAI target at flowering.

4.4.1.2. Crop N content and GAI at different GSs

When grouping the GSs into three categories (pre-stem to stem elongation, stem elongation to flowering and post flowering) across all years and SDs, the linear regression of GAI against crop N content value yielded a single fitted linear equation (Figure 4.2- B) as the best fit option. Across all years and all GSs, each unit of GAI had an N content equivalent to 53.40 kgN/ha of crop N for 1 unit of GAI (Table 4.3).

4.4.1.3. Crop N content and GAI at flowering (GS 65)

The relationship between crop N uptake and GAI at flowering stage was significant at the individual SD level across site-years. According to Table 4.3, SD1 had an N content of 54.6 kg/ha per unit of GAI. Sowing date 2 had a value of 53.40 kgN/ha, whereas SD3 had just 43.8 kg N/ha/ GAI unit formation with the steepest slope (Figure 4.2-C).

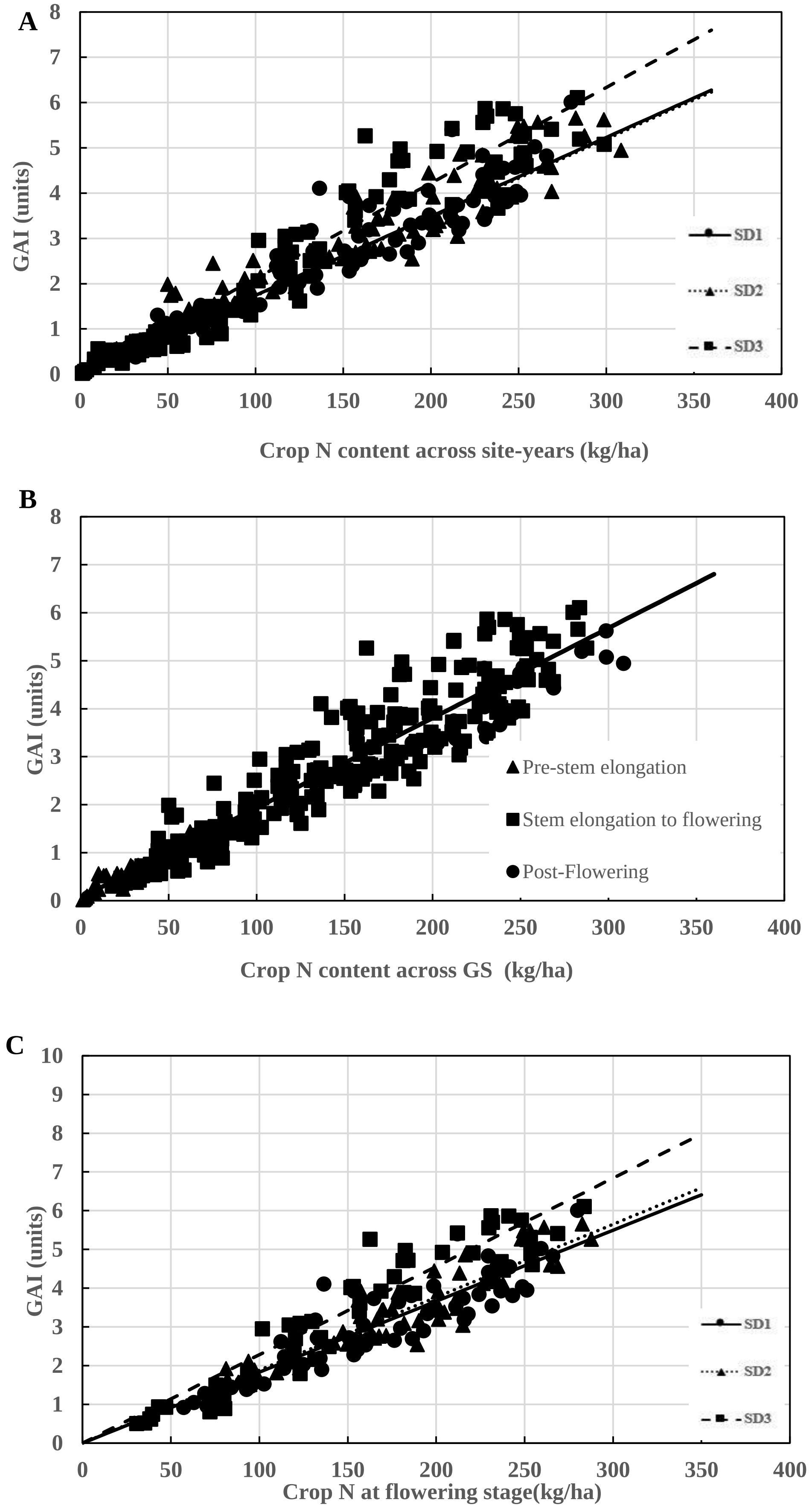


Figure 4.2-A to C: Regressions between crop N content and GAI at different groupings

Table 4.3. Multiple linear regression coefficients grouped by three different variates, firstly by SDs across years, then by different GS, and thirdly by SDs at flowering stage (GAI= Crop N at flowering*a + b), where "a" is the slope and "b" shown as intercept (constant). Nitrogen uptake at 1 unit of GAI and also a target value of 4 were also calculated. Standard Error of observation and degrees of freedom are shown as S.E. (df). Mean values and S.E.M. is the standard error of the mean among variates, Adjusted R^2 is also mentioned.

	Source of variant	Slope (a)	Intercept (b)	N uptake kg/ha/GAI	N uptake per 4 units of GAI (kg/ha)
Across years and growth stages	SD1	0.0174***	0.085 ns	57.4	229
	SD2	0.0173***	0.245*	57.8	231
	SD3	0.0211***	-0.057 ns	47.3	189
S.E. (df)	0.474 (309)				
adj. R^2	0.945				
Mean (S.E.M.)				**54.1 (2.46)**	**216**
All GS		0.0187***	0.0592ns	53.4	213
S.E. (df)	0.511 (309)				
adj. R^2	0.895				
GS 57 to 65	SD1	0.0183***	-0.061ns	54.6	218
	SD2	0.0187***	-0.004ns	53.4	213
	SD3	0.0228***	-0.176*	43.8	175
Mean (S.E.M.)				**50.6 (2.92)**	**202**
S.E. (df)	0.501 (204)				
adj R^2	0.871				

Comparison using a paired t-test between slopes and intercepts, *P* levels of <0.001*, <0.01** and < 0.05***

4.4.2. The relationship between GAI and FI

In Table 4.4, the GAI to achieve 95% FI is presented along with a GAI range with upper and lower values determined by 95% confidence limits, for all of the site/year data. Also, Figure 4.3 illustrates the related exponential curves for individual years (A to C) and across years (D). The relationship between the closest N strategy, its N rate and the corresponding 0.95CI optimum GAI is tabulated in Table 4.5.

According to Table 4.4 and Figure 4.3-A to C, no significant difference in the relationship between GAI and FI was found among SDs. For site-year 1 the optimum GAI was 4.08. The CMs which produced canopies within the optimum GAI range were CMStd at SD1 (with 110 kgN/ha), Fix225 and CMStd for SD2 (165 kgN/ha) and SD3 (CMStd, 200 kgN/ha) and CMHiY (260 kgN/ha). In site-year 2, 4.38 was the optimum GAI with a range of [4.10 to 4.66], and with CMHiY, Fixed225 and CMStd included values of 224, 225 and 140 kgN/ha, respectively for SD1, SD2 and SD3. In site-year 3, optimum lower and upper limits of GAI were between 3.93 and 4.50, with CMStd, Fixed225 and CMHiY giving the closest GAI values (Figure 4.3-C, Table 4.5).

When considering all years together, three SDs were obtained (Table 4.4, Figure 4.3-D). The N strategies which gave the optimum GAI were mainly Fixed225, CMHiY, and CMStd as site-year 3 treatment (Table 4.5).

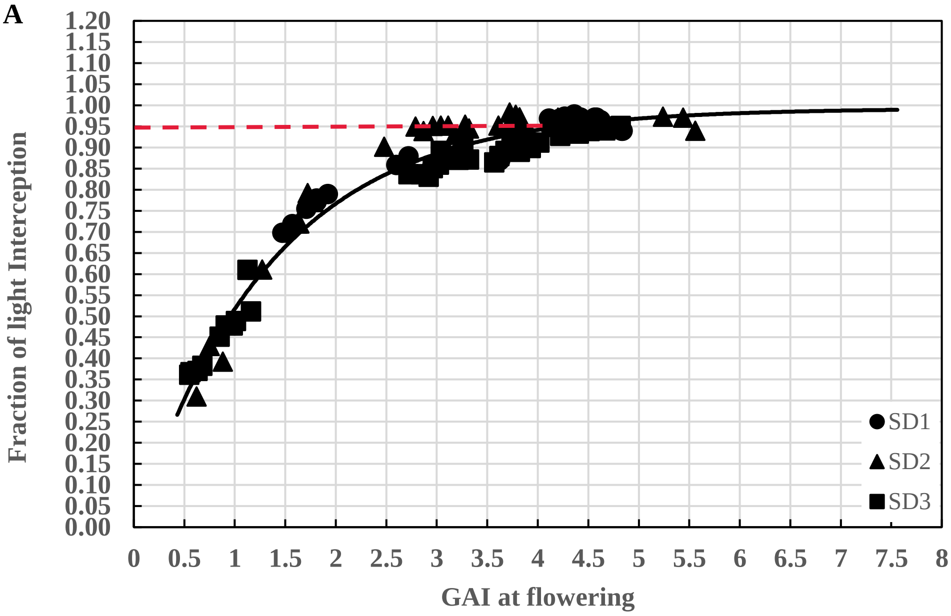
Notably, as the regression between GAI and FI differed significantly between site-years, so did the k value. Values were 0.670, 0.705 and 0.743 respectively from year 3, year 2 and year 1. When all years were considered, the extinction coefficient was highest at 0.786.

Table 4.4. The relationship between GAI and FI ($FI=1-e^{-k*GAI}$), with the fitted exponential curve parameters, SE is the standard error of the observation (df) defined the degress of freedom, adjusted R^2. Significant stepwise analysis was run on individual year and three different SDs across year. GAI unit was calculated at 95% of maximum FI and its 0.95 lower and upper limits shown as []

Site-years	K	SE (df)	GAI unit at 95% of FI	GAI unit within 95% CI	adj.R^2	P-value
Site-year1	-0.743	0.042 (97)	4.08	[3.95, 4.18]	0.942	<.001
site-year2	-0.705	0.062 (69)	4.38	[4.10,4.66]	0.756	<.001
site-year3	-0.670	0.030 (82)	4.21	[3.93, 4.50]	0.958	<.001
All years	-0.786	0.048 (250)	3.80	[3.54,4.05]	0.892	<.001

(e as Napier constant, 2.781)

A


Fraction of light Interception
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
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0.20
0.15
0.10
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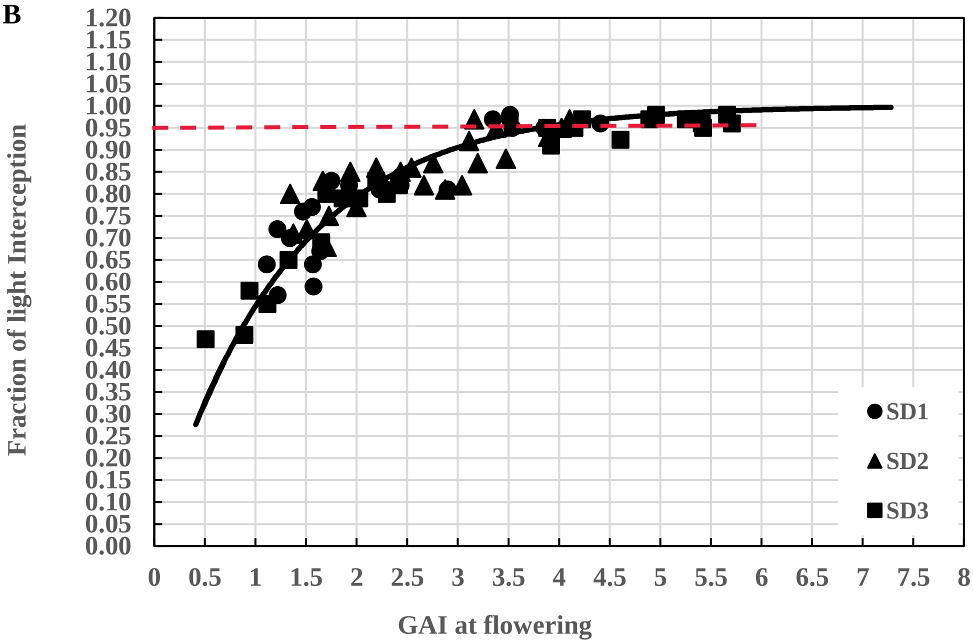
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8
GAI at flowering
SD1
SD2
SD3

B


Fraction of light Interception
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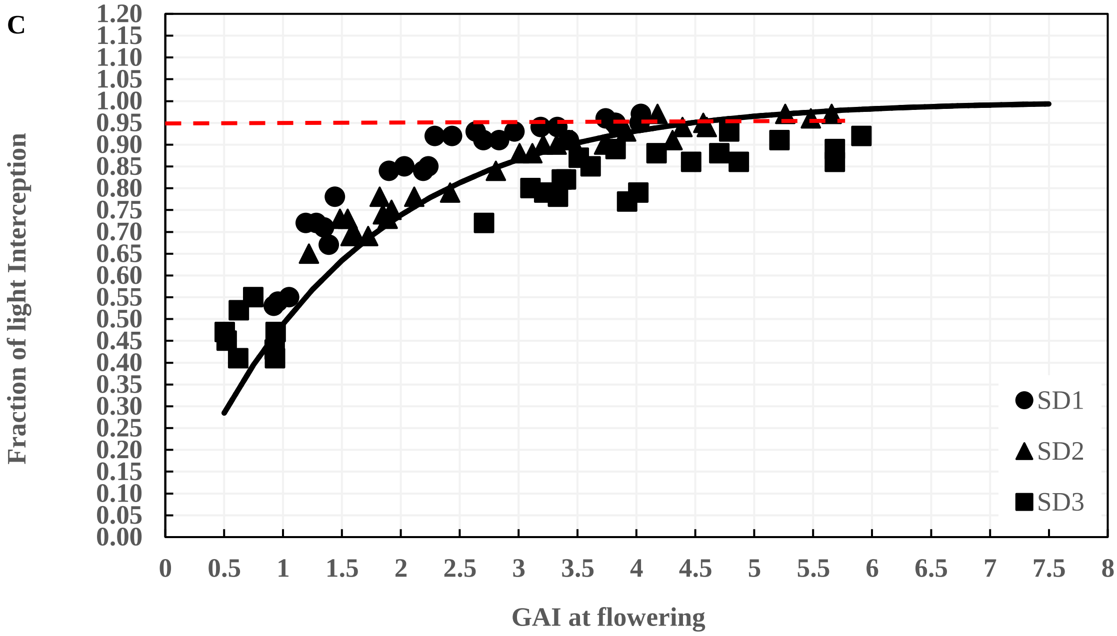
GAI at flowering
SD1
SD2
SD3

C



D

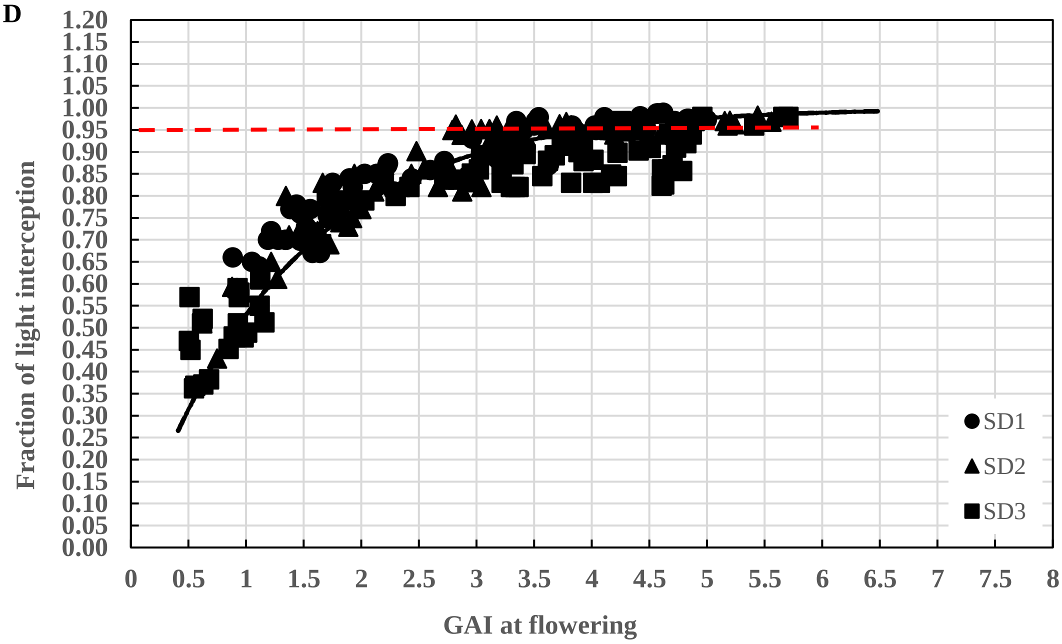


Figure 4.3-A to D: Regression between GAI and FI in year 1 (A), year 2 (B), and year 3 (C) ; (D) shows all three years data. Dashed red line showing 0.95 FI.

Table 4.5. Nitrogen strategies and their N rate for each individual year and SD, correspondent to the measured optimum GAI at 0.95CI of 95% of FI

Year	FI~GAI		
	SD	N strategy	N rates (kg/ha)
Year1	1	CMStd	110
	2	Fix225	225
		CMStd	165
	3	CMHiY	260
		CMStd	200
Year2	1	CMHiY	224
	2	Fixed225	225
	3	Fixed225	225
		CMStd	140
Year 3	1	Fixed225	225
		CMHiY	200
		CMStd	140
	2	Fixed225	225
		CMHiY	187
		CMStd	127
	3	CMHiY	261
		CMStd	201

4.4.3. The relationship between GAI and seed yield

The relationship between yield and GAI differed in a similar way to the previous section (4.4.2) in terms of SD within each site year, related coefficients and figures are gathered in Table 4.6 and Fig. 4.4- A to D.

In site-year 1 and 2, sowing date did not have a significant impact on the stepwise regression; therefore, a single linear plus exponential curve was fitted for each year (Figure 4.4- A and B). The GAI values at 95% of maximum yield were 4.20 and 3.39 in year 1 and year 2 respectively (Table 4.6). The corresponding N strategies within the optimum GAI range are also shown in Table 4.7.

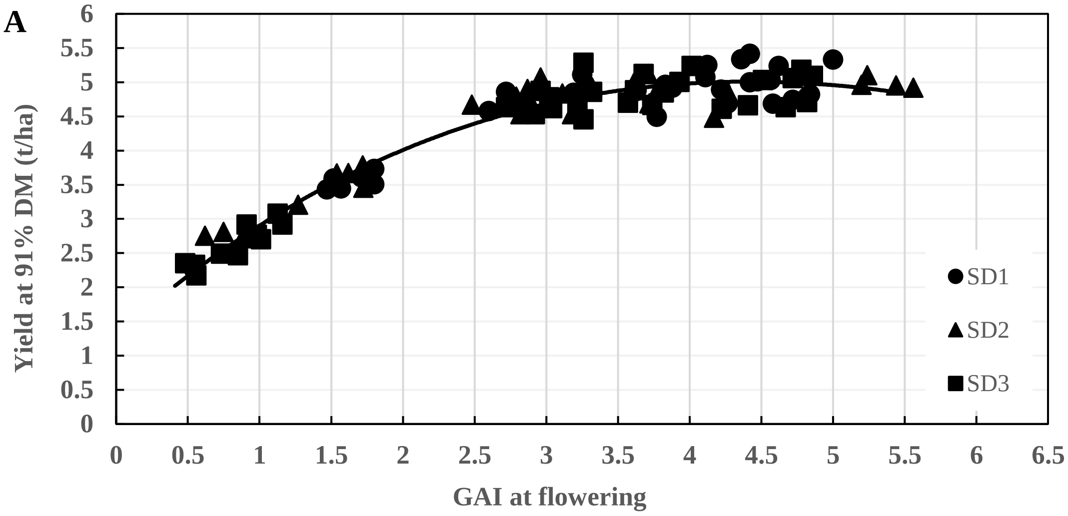
The two years had a broad range of GAI from [3.83 to 4.57] and [2.56 to 4.21] within 0.95 CI measured on year 1 and 2, for which corresponding N strategies were Fixed225, CMHiY, CMStd, and CMLo on year 2/ SD2 (Table 4.7).

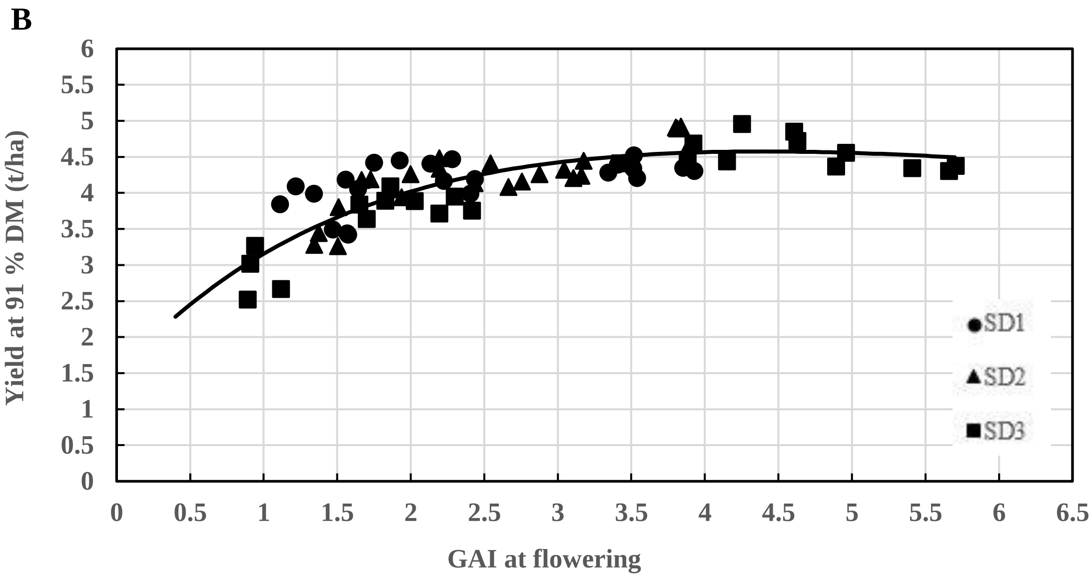
In year 3, sowing date had an impact on the regression, which was observed as three non-parallel lin+expo curves. Maximum yields limited to 4.58 t/ha in SD3, compared to 5.37 t/ha and 5.57 t/ha in SD1 and SD2, respectively. In this year, the lower limit of the 0.95 CI range was 2.64 unit of GAI in SD1 including CMStd. The highest value of GAI related to the the SD3 from 4.28 to 5.84. In year 3 the corresponding N strategies were Fixed225, CMHiY and CMStd (Tables 4.6 and 4.7).

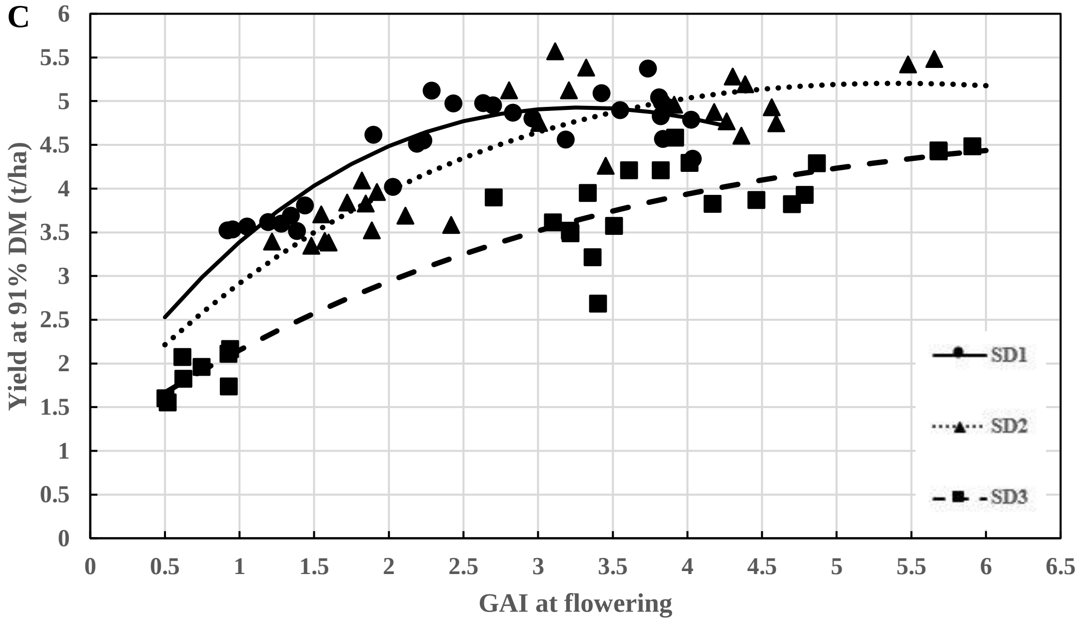
Stepwise regression was significant on individual SDs across years and notably, optimum GAIs at 95% of maximum yield increased as SD was delayed. The values of GAI 3.69, 4.01 and 4.32 were calculated for SD1, SD2 and SD3. According to Table 4.7, the three common N strategies were in the optimum range, but notably, IrishCM with the least amount of N of 104 kgN/ha was also included for SD2 when considering across year figure (Table 4.6).

Table 4.6. The relationship between GAI and yield (Yield= A+BR^{GAI}+C×GAI), with the fitted linear + exponential curve parameters; SE is the standard error of the observation, adjusted R^2. Significant stepwise analysis was run on individual year and three different SDs across year; GAI unit was calculated at 95% of maximum yield and its 0.95 lower and upper limits shown as []

Site-year	SD	Curve parameter				SE (df)	GAI at 95% max yield	GAI 95% CI related to 95% Max. yield	Max Yield	adj. R2	*P*
		A	B	C	R						
Site-year 1		29.8	-28.5	-2.16	0.868	0.215 (97)	4.20	[3.83,4.57]	5.41	0.836	<0.001
Site-year2		17.4	-14.9	-1.16	0.862	0.351 (70)	3.39	[2.56,4.21]	5.15	0.557	<0.001
site-year3	1	18.2	-16.7	-1.85	0.772	0.229 (82)	3.08	[2.64,3.52]	5.37	0.906	<0.001
	2	10.8	-9.42	-0.604			3.60	[2.99,4.22]	5.57		
	3	6.23	-5.13	-0.119			5.06	[4.28,5.84]	4.58		
Across years	1	6.65	-5.21	-0.237	0.616	0.389 (251)	3.69	[3.08,4.30]	5.42	0.776	<0.001
	2	6.51					4.01	[3.33,4.67]	5.57		
	3	6.21					4.32	[3.86,4.79]	5.28		


A
Yield at 91% DM (t/ha)
GAI at flowering
SD1
SD2
SD3
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5


B
Yield at 91 % DM (t/ha)
GAI at flowering
SD1
SD2
SD3
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5



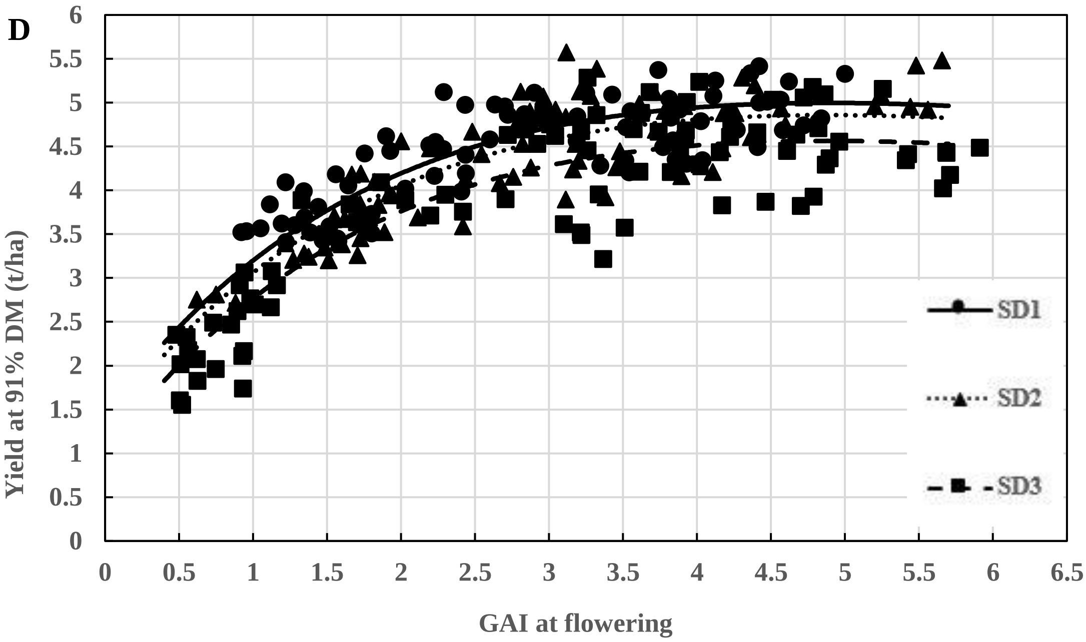


Figure 4.4- A to D: Regression between GAI and yield relationship in year 1(A), year 2 (B) and year 3 (C) across years (D) grouped by SDs

Table 4.7. Nitrogen strategies and their N rate for each individual year and SD, correspondent to the optimum GAI at 0.95CI of 95% maximum yield

		Yield~ GAI	
Site-years	**SD**	**N strategy**	**N rates (kg/ha)**
Year 1	1	Fixed225 CMHiY CMStd	225 170 110
	2	Fixed225	225
	3	Fixed225 CMHiY CMStd	225 260 200
Year2	1	Fixed225 CMHiY	225 224
	2	Fixed225 CMHiY CMStd CMLo	225 205 145 61
	3	Fixed225 CMStd	225 140
Year 3	1	Fixed225 CMHiY CMStd	225 200 140
	2	Fixed225 CMHiY CMStd IrishCM	225 187 127 104
	3	Fixed225 CMHiY CMStd	225 261 201

4.5. Discussion

In the current study, the quantity of above ground crop N associated with one unit of GAI fluctuated among SDs across site-years with values of 48.0 kgN/ha, 54.2 kgN/ha and 56.2 kgN/ha on SD3, SD2, and SD1, respectively. There was no variation in this relationship from pre-stem GS up to post-flowering and there was a consistent recorded value of 52.5 kgN/ha/GAI. Therefore, if a GAI of 4 unit is optimum, an uptake of 210 kgN/ha is needed at flowering GS.

Considering SD difference at flowering GS, the lowest value related to the SD3 with 45.7 kgN/ha/GAI whereas SD1 and SD2 had 55.2 and 53.5 kgN/ha/GAI at flowering stage.

In the UK experiment conducted by Berry and Spink (2009b) crop N uptake for forming 1 unit of GAI at flowering was calculated only as a slope with the value of 43 kgN/ha, with R^2 explained the variations by 0.74. For simple practice, authors concluded 50 kgN/ha/GAI as s a practical estimated figure to use in calculating WOSR crop N demand. Consequently, the figures produced from this study will result in a very similar base for fertilizer recommendations.

In the continental humid climate of north part of Germany, GAI was also shown to be linearly correlated to N uptake, yet each GAI unit was measured as 36 kgN/ha under different N applications. Shorter winter growth and colder winter temperatures resulted in less available N uptake. There was also a statistically similar value at various GS from stem elongation to the end of flowering (Weymann *et al.*, 2017). The author showed that different N rates did not influence the GAI and N uptake relationship, similarly, this current experiment indicated that either zero-N application or N rates of 260 kgN/ha were not significantly different for crop N per GAI unit; also one value was calculated from pre-stem to post flowering GS. The reason is WOSR is able to reduce leaf mass per unit of crop mass, so as to relocate the assimilations to the stem under critical N conditions. In situations where there is no water deficiency (as in a maritime climate), the expansion of leaves will continue simultaneously with a stable rate of photosynthesis per unit leaf area; as the rate of photosynthesis is not changed, the crop will not invest more N on leaf expansion unless a decrease in photosynthetic per unit leaf area occurs (Lemaire *et al.*, 2008). Furthermore, even on low N availability, the WOSR leaf expansion will continue with a stable rate of photosynthesis according to Gammelvind *et al.* (1996).

The optimum GAI at flowering is considered to be achieved when 95% fractional interception is attained both according to Beer-Lambert`s law (algebraic point of view) and the measurements from Lunn *et al.* (2001). The adequate light interception depends on intercepting enough light on the upper layers of the canopy and the extinction coefficient (k) (McWilliam *et al.*, 1995; Stafford, 1996). When leaf area index is <1.75, photosynthesis is high as “k” is small and leaves are still in erect shape. At this stage, the amount of light the crop intercepts is more important than an even distribution at low density over all the leaves (corresponds to the start of the curve, close to maximum value). When GAI increases, “k” is increasing, so the interception is virtually completed (in the plateau part of the curve). From this stage onwards, photosynthesis is mainly related to the even distribution of the intercepted radiation where the height and the thickness of the leaves has changed to a more prostrate form (Monteith, 1965). In this study, the measured extinction coefficients were in the range 0.60 to 0.78, within UK and French values (Gabrielle *et al.*, 1998; Justes *et al.*, 2000; Mendham and Salisbury, 1995; Mendham *et al.*, 1981b). In site-year3 the k value was the smallest (=0.670) and the 0.95 CI becomes bigger as there was a delayed SDin this site-year. The smaller k value in this year meant there was scope for more canopy growth as there was a higher possiblity of light interception and higher (continous) photosynthesis. In a similar study by Stafford (1996), GAI and intercepted light were studied with stratified WOSR layers. It was found that light penetration was inversely related to the k value. When a canopy is sparser, there is higher interception within the canopy, k value is small, and leaves are erected.

The average GAI values across site-year on separated SDs in this study showed a minimum of 3.02 (from SD2) and a maximum value of 4.36 (from SD1) units at their 0.95CI of maximum

FI. In almost all site-years, the three N strategies of Fixed225 kgN/ha, CMHiY and CMStd achieved values within the optimum ranges (photos in Appendix 4). Therefore, for practical purposes, a GAI range of 3.50 to 4.50 can be set as optimum for intercepting 95% of FI for SD1 and SD2, as it also includes UK average values. However, for sowing dates of late Sept (within 20s) a range of 4.00 to 5.00 is shown to be optimum across years. It is debatable that depending on how late the mid-Sept is or how favourable weather conditions can be, the optimum range differs within a tighter CI, and SDs optimum points can be similar (i.e. year 1 and 2).

A wide range of 0.95CI on different site-years and SDs is to be expected through different variations affecting GAI formation such as plant population, water and N supply (Mendham and Salisbury, 1995). A typical range of 0.5 to 2.0 units of GAI at stem elongation to a maximum value between 2.0 and 7.0 at flowering has been noted on WOSR (Kirkegaard *et al.*, 2021). The UK optimum GAI of 3 to 4 at flowering (Lunn *et al.*, 2003a; Mendham and Salisbury, 1995), comprised of 2.5 units of leaf area and 1.5 units of green stem area has been proven to be sufficient for intercepting 90-95% of radiation (Berry and Spink, 2006; Lunn *et al.*, 2001). In the current study, the effect of sowing date was amplified where wider ranges of N rates were applied; for example, in site-year 3, five different rates from 44 kgN/ha to 261 kgN/ha were applied compared to four N strategies (57 kgN/ha to 225 kgN/ha) or three N strategies (110 kgN/ha to 260 kgN/ha) respectively in year 2 and year 1. Therefore, the canopy size needed to allow 95% of maximum yield at a broadened range. Data across years indicated that the GAI needed for 95% yield was 3.69, 4.01 and 4.32 respectively, for SD1, SD2 and SD3. The results between GAI and yield had fluctuations on individual site-years and SDs. In this case, also the wide range of applied N strategies of Fixed225, CMHiY, CMStd and IrishCM (estimated on SD2 and SD3 in year 3) caused varied values.

The range of 3.50 to 4.50 units of optimum GAI based on FI and yield means different N strategies can comparatively be preferred and chosen based on farmer`s practical point of view.

Lunn *et al.* (2001) noted that there was a limitation of yield for GAI <2 and >6 and authors generalized that in bright years a larger canpoy and in dull years small canopies will be optimal.

As described earlier, more favourable weather conditions occurred on SD3 in year 1 and year 2, wherease SD3 in site-year 3 coincided with more precipitation in Sept with 120 mm versus 95 mm and 55 mm for year 1 and year 2. Upper limits of optimum GAIs in year 1 and 2 were both >4 and interestingly lower limit of 0.95CI of this value in year 2 was 2.56 units; other lower limits <3 defined in site-year 3 on early SDs. Lunn *et al.* (2001) also showed a GAI of 3.5 sufficient for a yield of 4.2 t/ha with variation from 3 to 5 GAI units having little effect on yield. This was because in their study the seed rate varied from 60/m^2 to 120/m^2 for early to late SD, while notably in this current study, seed rate was studied at a constant value of 50/m^2 on all SDs, and perhaps not sufficient on SD3/ site-year 3.

Larger photosynthetic area at flowering meant improved yield formation; in this study achieved yields were higher than the UK in SD1 and SD2. If assumbly upper limits of 0.95CI are taken into account as crop N demand, i.e. 4.5 units, there would also be the possibility of disease and envirnomental conditions interfering with the yield to GAI relationship. Also an unforeseen increase in the soil moisture deficit (SMD) prior to harvest may induce yield reduction with more significant effects in bigger canopies. Therefore, from a practical point of view on SD1 and SD2, optimum GAIs can be from 3.50 to 4.5, and on SD3 a range of 3.5 to 5 can be valid as optimum range, although it is debatable to consider lower limits for environmental and economic reasons. Because a GAI close to 5 means bulky, short plants, with more branches and leaves for a delayed SD, high seed moisture interfers with harvest timing. Hence, on all types of SDs it is recommended to target lower 0.95 CI, providing that site-year soil/ weather conditions are known, as there would be the possiblity of AAN release, mainly on the latest sowing dates. Hence, a balance between late sowing date and physiological concepts of the plant is needed. Firstly, if the crop is sown late (20th Sept) there should be compensatory factors such as higher seed rates, but based on results from Chapter 3, AAN appears to compensate for the late sown plants. Therefore, higher N rates might not be a guranteed solution to meet the crop N demand. In this case, it is easy to under-estimate the spring SNS. Therefore, achieving an optimum GAI of 5.00 can still produce a favourable yield according to site-year specific results, but producing a bigger crop at late sowing date might be risky if dry conditions occur at harvest time, and general husbandry management (i.e. harvesting time) would be delayed

4.6. Conclusion

The presented results indicate that each unit of of GAI contains 54.1 kgN/ha when measured from pre-stem elongation GS up to post flowering. A slight variation was observed at different SDs. This is similar to the UK figure and confirms that this can be used as a basis for canopy management N calculations to determine post winter crop N uptake and the further uptake needed by flowering.

The optimum canopy for light interception and yield formation was higher than measured values in the UK; this probably is explained due to a greater yield potential and variations which occurred through different SDs (i.e. wider range of N application during years).

For earlier SD (Mid to End Aug) optimum GAIs (and 0.95 CI) were 3 to 4.5 across site-years, although optimum GAI of 2.56 was also obtained in 2018/19 (year 2). Where late sowing resulted in delayed plant growth and development, GAI values were shown to be as high as 4.28 to 5.84 for lower and upper 0.95 limits between economical optimum yield and GAI.The application of N fertilizer should target lower limits of 0.95CI as there is the possiblity of excess AAN. In the case of AAN release in the late sown crops, longer vegetation growth stage and late harvesting time can result in a yield penalty, and also potential economical and environemntal issues.

The N strategies which were known as optimum in this study, included at least the three typical N strategies (Fixed225, CMHiY and CMStd). An application of medium N rates of

CMStd would meet plant`s requirement for the maximum yield and desirable fraction of light interception even up to first 10 days of September.

5.0. Understanding the impact of winter defoliation on crop N uptake and yield in a mild climatic condition on WOSR

5.1. Abstract

Although it is proven that WOSR has a high potential to take up large amounts of N during winter, the impact of defoliation, including whether the cut residue is retained on the plot or not, on N dynamics and crop yield is not known in a milder climate. In this study, mid-winter defoliation practice was evaluated on WOSR sown at early sowing dates, to determine the defoliation impact on the subsequent final N uptake, yield, and yield components of WOSR. Using two-site-years (2018/9 and 2019/20) and two sowing dates: mid-Aug (SD1) and late August (SD2) and defoliation practice was implemented in January using a lawn mower on unfertilized (zero-N) and fertilized crops. To determine any impact of retaining the mown material on the plots, both retained (zero-Rt) and removed (zero-Rm) treatments were applied on zero-N plots. Non-defoliated plots with zero-N and fertilized (Canopy management N strategies and Fixed225) were set as control treatments. Early spring measurements (crop N, SMN, GAI) and harvest N uptake with NUE (including SNUpE and NUtE), yield and its components were studied on zero-N plots. Yield was regressed against all N strategies on a linear plus exponential curve for year 2019 and 2020 to define if the optimum N rates (Nopt) and the maximum economical yield values differ between defoliated and non-defoliated treatment. Results showed, spring SNS and final N uptake could vary depending on site-year and defoliation type (Rm or Rt). Canopy size was reduced by 44% in 2019 and 30% in 2020 by defoliation. Plant residuals on zero-Rt were not able to decompose and recycle to the crops by harvest in site-year 2019, whereas in 2020, harvest N uptake on zero-Rt was numerically higher than zero-Rm crops and as high as zero-Non. On fertilized defoliated plots, in 2019 an additional 47 kgN/ha was needed to achieve same yield as non-defoliated plots. Whereas, in 2020 yield reduced by 0.49 t/ha for the same Nopt. The impact of defoliation was season dependent: the

most severe defoliation (to a GAI <0.4), as in 2020 resulted in non-recoverable yield loss and both years needed additional N application.

5.2. Introduction

Ireland by far has the highest proportion of GHG emissions in the EU as a result of agriculture sector activities; about 50% of the total emission is related to non-CO_2 GHGs namely, methane (CH_4) and nitrous oxide (N_2O) according to the Intergovernmental Panel on Climate Change (IPCC, 2021). In this country, agricultural GHG emissions have increased by 3.8% between 2005 and 2019 (EPA, 2020), and if required actions are not taken, emissions from agriculture will increase by 9% by 2030 (compared to 2005). This increasing challenge contradicts Ireland`s national policy goal for carbon neutrality in agriculture by 2050 (Läpple *et al.*, 2022), mainly by increases in dairy cow numbers and N fertilizer use (Lanigan *et al.*, 2018). To reduce the contribution of agriculture GHG emissions there are some practical solutions (Smith, 2008). Sequestrating soil C is projected to reduce 90% of global emission related to agriculture by 2030 (Smith *et al.*, 2007); also increasing soil productivity by alleviating nutrient deficiencies either by fertilizer or organic amendments enhances plant litter returns and soil C storage (Conant *et al.*, 2001; Schnabel *et al.*, 2001). In parallel with soil productivity, nitrogen use efficiency (NUE) of crops should be improved by increasing crop yield without increasing fertilizer N use, or ideally by reducing fertilizer use (Sylvester-Bradley et al., 2015). Where yield on unfertilized plots is high, using lower rates of N is necessary to achieve higher N use efficiency (Defra, Evidence Project Final Report, EVID4, 2015). This indicates the scope for more efficient N use with more precise N management practices, without considering the longer term potential of genetic improvement of the target crop.

In a mild climate, WOSR actively takes up N over winter to build canopy N in the plant biomass. In chapter 3, soil N uptake efficiency (SNUpE) was shown to be slightly greater than 100% when the crop was early sown, but significantly higher on late sown crops. Hence, it is doubtful if the same pattern of N uptake would occur among less-developed spring canopies due to defoliation (as an imitation of pigeon damage). Crop recovery from vegetation damage through grazing and hand cutting has been studied on *Brassica napus* L. in Australia and Canada as an imitation of animal grazing (Kirkegaard *et al.*, 2012), where there was a complete yield recovery in early stage defoliation in Australia due to sufficient time and favourable conditions for biomass recovery. Defoliated crops in the same study in Canada, did not recover for seed yield formation in spite of similar time of maximum LAI in both regions. Also, Ulas *et al.* (2015) observed that defoliation at GS 61 (early flowering) resulted in a yield decrease on different N rates and cultivars, due to a reduction in N uptake in the leaf removal process, in a climate (Gottingen, Germany) where post-flowering growth and N uptake were significant.

Leaf loss through mechanical damage (defoliation) is a novel approach for assessing the effect of pigeon damage in a mild climate. There is an unanswered question about the N demands and recovery capacity of WOSR crops grazed over-winter by pigeons. Defoliation practice in a mild-continental climate of the UK, has been conducted on WOSR using a mower in January, to assess physiological traits, by Spink (1992). The observations indicated that while yield was not affected by defoliation, there was a slight reduction in overall vegetation production ($P \leq 0.05$). Defoliation has been shown to reduce seed production from the terminal raceme, instead higher branch numbers and more seed formation from the lower parts of plant compensated for the main raceme seed production (Spink, 1992; Lardon and Triboi-Blondel, 1995). Also, the fate of the N removed during defoliation, if retained in the field, needs to be determined to test if this N loss would result in recycling back to the plants at milder climates. In French studies, dropped leaves in winter, did not affect SMN content at flowering or harvest as the ^{15}N-labelling tests showed losses of 40% gaseous emission on a site-year basis (Dejoux *et al.*, 2000).

As described in chapter 3, there are possibilities of predicting N fertilizer through the UK-CM system by assessing soil N supply, required canopy size and yield potential, to determine how much fertilizer N was required. Yet, defoliation through pigeon attack raises questions about the consequence of the lost vegetation and its impact on yield. Moreover, where crops are defoliated, it is not known if retaining the defoliated material on the soil (as a potential source of organic material) results in a different N uptake compared to where the residue is removed.

The aims of this study are to compare spring SNS, harvest N uptake, soil N uptake efficiency, N use efficiency, yield and yield components on unfertilized defoliated (with both removed and retained plant residuals from mowing) and non-defoliated crops. This will determine the potential for plant debris N to be recycled into the crop and to compare the effect on harvest N uptake and subsequent yield. This work will also determine any difference between Nopt and maximum economical yield on defoliated and non-defoliated plots on all fertilized and non-fertilized crops, and test if winter defoliation would require higher N application.

5.3. Materials and methods

5.3.1. Experiment

Two WOSR field experiments were conducted over 2018/9 (sampling year 2019) and 2019/20 (sampling year 2020) on sites where winter barley was grown in the year prior to the experiment in Oak Park- Carlow.

The experiment`s design, site and year characteristics were described in previous chapters. To test the experimental hypothesis concerning defoliation, data from SD1 and SD2 on unfertilized treatments were tested for their spring SNS, SNUpE, harvest N uptake,etc. In addition, fertilized and unfertilized SD1 and SD2 yield data were regressed against N rates on both defoliated and non-defoliated crops to compare maximum economical yield difference separately for each year. Crops from SD1 and SD2 were considered as one set of data in each of two years (2019 and 2020) to analyse, because later sown crops (SD3) did not produce sufficient biomass to allow defoliation have an effect. .

The experiment used a split-plot design with main plots as the two sowing dates (SD1: Mid Aug and SD2: End Aug), and N management strategies: (UK-CMs), Fixed225 and zero-

N in combination with defoliation practice as subplots, and four replications in a block structure (Table 5.1.). Subplot dimensions were 21 m× 6 m; the variety used was Anastasia, sown at 50 seeds/m^2. Calcium ammonium nitrate (CAN, 27%) was used as the inorganic fertilizer N source for all experiments and was applied to individual plots using a full-width plot applicator.

5.3.1.1. Defoliation and net coverage on plots

Defoliation was carried out using a lawn mower (Kubota G23HD) in winter when weather permitted (2nd of January in 2019 and 23rd January for 2020). The cutting level was set to remove leaf material with an attempt not to damage the growing point, although sometimes unintentionally this part was removed (Figure 5.1-B).

Two separate defoliation practices were evaluated on the zero-N plots: one where the cut material was returned immediately to the plot, by diverting the flow from the lawnmower to the ground (zero-Rt) (Figure 5.1- D), and the second where the cut material was removed, by catching the cut materials in the mower container (zero-Rm) (Figure 5.1-A and C).

Subplots, which were not defoliated, were covered during late autumn/ early winter with bird protecting net type (15 mm× 15 mm hole size and a shading value of ≤ 1%), adjusted to the subplot dimensions, and pegged to the ground as the control non-defoliated plots (Figure 5.1. C).

Table 5.1. The experimental design using two SDs, with defoliated (including zero-Rt) and non-defoliated N strategies

Site-years	N strategy rates (kg/ha)	Sowing Dates↓					
		SD1			SD2		
		Defoliated		Non-Defoli-ated	Defoliated		Non-Defoliated
		Rm	Rt		Rm	Rt	
Year 2019	Fixed225	225	-	225	225	-	225
	CMHiY	294	-	224	286	-	205
	CMStd	234	-	164	226	-	145
	CMLo	151	-	81	143	-	61
	Zero-N	0	0	0	0	0	0
Year 2020	Fixed225	225	-	225	225	-	225
	CMHiY	266	-	200	258	-	187
	CMStd	206	-	140	198	-	127
	CMLo	123	-	56	115	-	44
	Zero-N	0	0	0	0	0	0

↓Data from the two sowing dates (SD1 and SD2) were analysed as one set

Figure 5.1-A to D; A: Difference between defoliated and non-defoliated on SD1 crops- B: Samples of defoliated crops (the defoliated growing point on the right, and the defoliated rossette leaves on the left)- C: Plots with net coverage and defoliated removed material (Rm) - D: Plant defoliated materials retained on the plot (Rt)

5.3.2. Measurement

Similar measurement procedures described in previous chapters were used to determine canopy structure (GAI, biomass, N content) in early spring and at approximately two to three weeks before harvest.

Measuring crop N content using the Dumas method and GAI in early spring was through photos analyzed by BASF™ online tool services website (as described in previous chapters) for zero-Non (not-defoliated, not-fertilized) and defoliated on zero-N plots (zero-Rm and zero-Rt) crops. Crop N content of zero-Rt plots was considered similar to zero-Non plots, because the N analysis was not practically measurable on left over materials. In terms of GAI, zero-Rm and zero-Rt were counted similarly as one value, for the fact that photo GAI calibration tool had not been set up for the purpose of including plant debris on the soil in a photo.

Soil sampling was in mid to late February, depending on weather suitability, to analyse NO_3-N (mg/kg) and NH_4-N (mg/kg) using KCl- solution extraction method (Scharpf and Wehrmann, 1976).

Pre-harvest sampling was described in chapter 3, and N content analysis on ground plant materials was performed at plant growth stages of GS 35 and GS 85 using the Dumas analysis (Rapid N Cube, Elementar Analysensysteme, Hanau, Germany). Total biomass measurement, based on the separated plant components, leaves and stems (and pods at GS 85) was calculated as the sum of all plant fractions which were oven dried at 75˚ C for 72 h. Following drying, pod walls were separated from seeds, allowing the ratios of pod wall to seed weight, and stem to seed weight to be taken into account for final biomass calculation.

Seed yield was quantified by harvesting a 2.75 m wide full plot length strip using a plot combine harvester (Deutz Fahr 37.10) on 1st August 2019 and 28th July 2020. Seed moisture was determined using a Dickey John GAC2000 Grain Analysis Computer (Auburn, Illinois, USA). Seeds were counted for thousand seed weight (TSW) in gram (g) using a Baumann Saatzuchtbedarf Contador grain counter (Buchenstrabe 11, d-7112, Walderburg, Germany).

Seeds/m^2 was obtained from TSW and seed weight/m^2 at 91% dry matter. Pod number/m^2 was achieved by counting pods in 0.04 (from a sub-sub pre-harvest sample, GS 85). In addition, pods/plant was calculated counting the number of plants/m^2 when sampling at that GS knowing the pod/m^2 figures. Finally, a seeds-per-pod value was derived from the number of seed/m^2 and number of pod/m^2.

5.3.3. Calculation and analysis

N use efficiency was calculated as the yield to the N supply ratio by Moll *et al.* (1982) on both fertilized and zero-N crops (Equation 5.1.).

$$\text{NUE}\left(\frac{\text{kg}}{\text{kg}}\right) = \frac{\text{seed yield}}{\text{N supply}} \qquad \text{(Eq. 5.1.)}$$

NUE, by this definition includes either N uptake efficiency from soil (SNUpE) which is described on zero-N plots or fertilizer N uptake efficiency (FNUpE) on fertilized plots. Another measurement as the second part of NUE, is the N utilization efficiency (NUtE) which is the ability of crops to utilize the taken up N to produce seed yield. The NUtE follows the equation 5.2.(Horst *et al.*, 2003; Masclaux-Daubresse *et al.*, 2008).

$$\text{N utilization efficiency}\left(\frac{\text{Kg}}{\text{Kg}}\right) = \frac{\text{seed yield}}{\text{total N uptake}} \qquad \text{(Eq. 5.2.)}$$

Soil N uptake efficiency followed the same equation as used in chapter 3 (Eq.5.3- A and B) Also, soil N supply on Zero-Rt plots was considered similarly to Zero-non plots, to test the hypothesis if SNUpEs of below would be any different from one another (Equation 5.3.)

$$\text{SNUpE}_{\text{Zero Plots } \textbf{(Non-defoliated and Rt)}} = \frac{\text{Total N uptake}}{\text{Crop N in spring+SMN}} \qquad \text{(Eq.5.3-A)}$$

$$\text{SNUpE}_{\text{Zero Plots } \textbf{(Defoliated)}} = \frac{\text{Total N uptake}}{\text{Defoliated crop N in spring+SMN}} \qquad \text{(Eq.5.3-B)}$$

Analysis of variance was run using Genstat 19.1 (www.vsni.co.uk), for which block and SD were random effects. Each year was separately analyzed for zero-N strategies, and the interaction of year and zero-N to define the levels of significance using ANOVA analysis with

S.E.D. as standard error of difference. Also lettering for significant mean differences as post-hoc practice was based on Bonferroni mean difference using Genstant.

Regression analysis was carried out using a liner + exponential (lin+expo) curve fitted to regress N application on defoliated and non-defoliated plots in response to yield grouped by year (Equation 5.4).

$$Y = A+BR^{N}+ C\times N \qquad \text{(Eq. 5.4)}$$

Where Y is the yield, A, B, C and R, are constant parameters. A stepwise regression process was followed on defoliated and non-defoliated plots for 2019 and 2020 in four consecutives steps as described in previous chapters, based on sum of squared error optimization. On both years, defoliation treatments were fitted as separated curves for the best fitted lin+expo model. The economic optimum N rate (Nopt) was then calculated using equation 5.5. The value of K used was 2.44 (based on the fertilizer and seed values from 2013 to 2020)

$$Nopt= \frac{[\ln\left(\frac{K}{1000}-C\right)-\ln(B(\ln R))]}{lnR} \qquad \text{(Eq. 5.5)}$$

5.4. Results

5.4.1. Zero-N defoliated (Removed and Retained) and Zero-Non

In Table 5.2, the impact of defoliation, with material removed (zero-Rm) or retained (zero-Rt) compared to non-defoliation (zero-Non) on a range of efficiency parameters and crop yield are presented. The difference in canopy sizes, shown as GAI, is significant on each individual site-year. The measured GAI on zero-Rm and zero-Rt in 2019 showed about 44% reduction from zero-Non. In 2020, the defoliation on zero-Rm and zero-Rt reduced the canopy size to 30% of the zero-Non.

Considering crop N content of zero-Non and zero-Rt assumed as same in early spring, the crop N content in zero-Rm was reduced by 27% in 2019 and 51% in 2020 comparing to zero-Rt and non-defoliated treatments ($P<0.01$, for year and treatment interaction). In 2019, on average, defoliation (zero-Rm) reduced the crop N content by 14.5 kgN/ha compared to zero-Rt/ zero-Non, whereas this value in 2020 was almost twice that at 27.8 kgN/ha of crop N reduction.

The SMN for each year was added to crop N for SNS calculation and where the defoliated material was returned to the soil surface, the equivalent crop N that was removed during defoliation was also considered potentially available as SNS. The effect of year or its interaction with treatment was not significant, but the defoliation strategies differed from one another (P-value <0.001) on SNS values. From Table 5.2 it is implied that in 2019, final N uptake between zero-Rm and zero-Non was different by 6.7 kgN/ha, but a higher N difference, of about 14 kgN/ha, was measured on zero-Rm comparing to zero-Rt. The difference among the values was not statistically different in this year.

In 2020, final N uptake on zero-Non was significantly higher by 20 kg/ha than zero-Rm. But the difference between zeroRt and zeroRm was 14 kgN/ha (similar to 2019) and insignificantly higher than zero-Rt.

In 2019, SNUpE was the highest at 1.42 on zero-Rm (due to smaller SNS) compared to zeroRt and zero-Non. The average soil N recovery rate (SNUpE) was 1.25 in this year compared to 1.08 in 2020 across zero-N treatments.

In terms of utilization of N on non-fertilized crops, no significant difference among treatments was observed in 2019, but in 2020, zero-Rm with 38.8 differed significantly from zero-Rt with 35.7.

Nitrogen use efficiency (NUE) as the ratio of seed yield to soil N supply, was numerically highest for zero-Rm in both years with 48 and 45% NUE, respectively in 2019 and 2020, but not significantly different from zero-Non crops. Yet, the meaningful difference was between zero-Rm and Rt with the zero-Rt resulting in poor efficiency comparing to zero-Rt crops.

Where no fertilizer N was applied, yield on the non-defoliated treatment had the highest numerical values but only significantly different from zero-Rt in 2020 and from zero-Rm in 2019.

Table 5.2. ANOVA analysis of early spring measurements, harvest N uptake, soil N uptake efficiency (SNUpE), N utilization efficiency (NUtE), N use efficiency (NUE), and yield on zero-Rm, zero-Rt, and zer-Non treatments, for each separated year, with P-value and S.E.D. (standard error of difference)

	Early Spring measurements					SNUpE	NUtE	NUE	Yield
Source of variations	**SMN**	**GAI**	**↓CropN (kg/ha)**	**SNS (kg/ha)**	**↓Harvest N uptake (kg/ha)**	**(kg/kg)**			**(t/ha)**
2019	23.0								
Zero-Rm		0.565^{b}	44.5^{b}	67.6^{b}	96.3^{ab}	1.42^{a}	34.2	48.0^{a}	3.26^{ab}
Zero-Rt		0.565^{b}	60.4^{a}	80.9^{a}	82.4^{bc}	1.04^{b}	37.2	36.8^{b}	2.93^{b}
Zero-Non		1.28^{a}	60.4^{a}	83.4^{a}	103^{a}	1.24^{ab}	33.8	41.3^{ab}	3.43^{a}
P-value		<0.001	0.003	0.007	ns	0.04	ns	0.031	0.042
S.E.D.		0.110	4.26	4.71	8.76	0.133	3.06	3.72	0.222
2020	39.0								
Zero-Rm	-	0.372^{b}	27.6^{c}	66.7^{b}	76.2^{c}	1.15	38.8^{a}	45.0^{a}	2.96^{b}
Zero-Rt	-	0.372^{b}	55.8^{a}	94.2^{a}	90.2^{abc}	0.97	35.7^{b}	34.5^{b}	3.12^{ab}
Zero-Non		1.21^{a}	55.8^{a}	91.1^{a}	96.2^{ab}	1.08	36.7^{ab}	39.5^{ab}	3.52^{a}
P-value		<0.001	<0.001	<0.001	<0.001	ns	0.031	0.007	<0.001
S.E.D.		0.058	2.62	5.56	4.45	0.081	1.14	2.92	0.152
Zero treatments (trt)									
Mean Zero-Rm		0.444^{b}	33.8^{b}	67.0^{b}	83.5^{ab}	1.25^{a}	36.5	46.5^{a}	3.11^{ab}
Mean Zero-Rt		1.23^{a}	56.0^{a}	87.5^{a}	87.3^{b}	0.998^{b}	36.4	35.6^{c}	3.02^{b}
Mean Zero-Non		1.24^{a}	57.4^{a}	87.2^{a}	98.8^{a}	1.14^{ab}	35.2	40.4^{b}	3.47^{a}
P-value(zero trt)		<0.001	<0.001	<0.001	<0.001	0.010	ns	<0.001	<0.001
S.E.D.(zero trt)		0.053	2.29	3.91	4.35	0.070	1.03	2.33	0.139
Year									
Mean 2019	23.0^{b}	1.01^{a}	53.8^{a}	77.1	95.4	1.25^{a}	34.7	42.8	3.25
Mean 2020	39.0^{a}	0.924^{b}	45.3^{b}	83.0	87.4	1.08^{b}	37.3	40.4	3.22
P-value (year)	<0.001	0.008	<0.001	ns	0.04	0.006	ns	ns	ns
S.E.D. (year)	1.44	0.047	1.91	3.26	3.63	0.058	1.07	1.92	0.114
zero trt × year									
P-value (zero trt ×year)	-	ns	0.006	ns	0.015	ns	ns	ns	ns
S.E.D. (zero trt ×year)	-	0.077	3.32	5.65	6.28	0.101	1.88	3.36	0.200

↓ Lettering is based on the significant zero-trt ×year interaction, or else based on the related significant P-value. Different letters indicate significant differences at P= 0.05 within a factor and parameter.

Yield component analyses of all unfertilized treatments are presented in table 5.3. Pod numbers differed between the two years: in 2019 the average number was 3,100 whereas, in 2020 pods reduced to 2,700 at harvest time. Generally, zero-Non treatments in both years had the highest pod number of 3,186 compared to circa 2,600 pods from the defoliated treatments. Other components associated with year effect were the TSW (g) and seeds/ pod. The TSW of 4.76 g in 2019 was significantly higher than in 2020. Other yield component affected by year for which 2020 showed higher values, was seed/pod with on average 28 seeds per pod compared to 24 recorded for 2019 for each m^2. It is also notable that seed weight /m^2 was influenced by the defoliation treatment as there is approximately 40 g seed weight difference among zero-Non, zero-Rt and Rm. In addition, there was no difference in most yield components between defoliation types (either Rm or Rt).

Table 5.3. The effect of defoliation treatment on yield components for 2019 and 2020

Source of variations	Yield Components			
2019	**Pod No./m2**	**[↓]TSW (g)**	**seedWt/m²(g)**	**seed No./pod**
Zero-Rm	2767[b]	4.69	325	25.8
Zero-Rt	3071[ab]	4.84	292	20.1
Zero-Non	3495[a]	4.76	343	20.8
P-value	0.04	ns	ns	ns
S.E.D.	270	0.063	22.2	2.34
2020				
Zero-Rm	2533	4.51	299[b]	27.4
Zero-Rt	2473	4.45	316[ab]	29.7
Zero-Non	3011	4.45	356[a]	26.9
P-value	ns	ns	<0.001	ns
S.E.D.	260	0.042	15.4	2.37
Zero-N treatments (trt)				
Zero-Rm	2618[b]	4.60[b]	309[b]	26.9
Zero-Rt	2689[b]	4.71[a]	308[b]	26.3
Zero- Non	3186[a]	4.60[b]	351[a]	24.7
P-value	0.004	0.031	<0.001	ns
S.E.D.	188	0.034	14.0	1.74
Years				
Year2	3123[a]	4.76[a]	325	23.7[b]
Year3	2707[b]	4.48[b]	327	28.4[a]
P-value	0.009	<0.001	ns	<0.001
S.E.D.	155	0.039	11.6	1.44
Zero-trt×year				
P-value	ns	0.020	ns	ns
S.E.D.	296	0.055	20.2	2.51

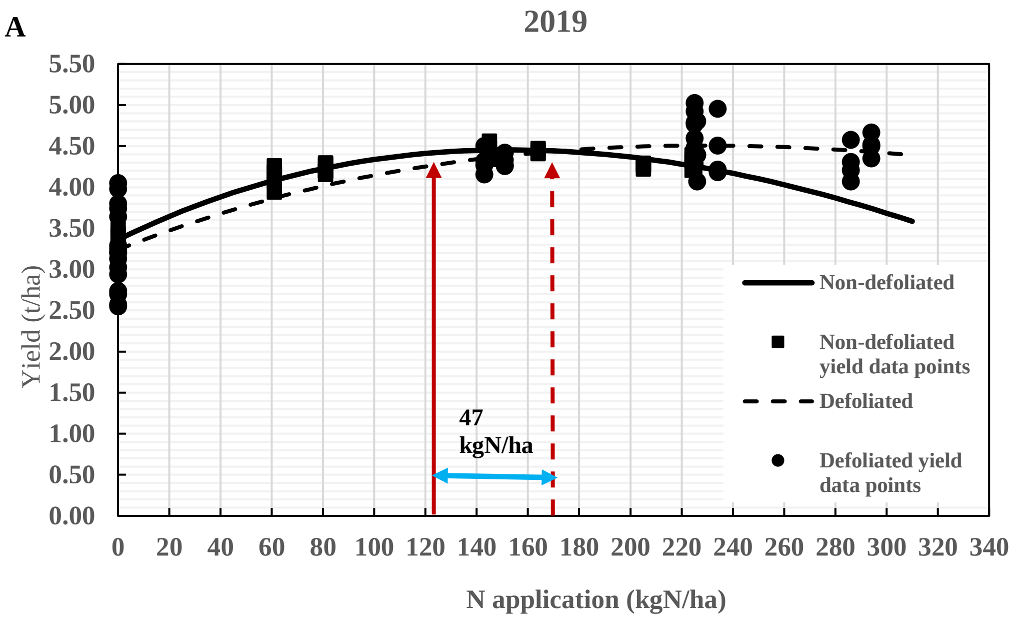
[↓] Lettering is based on Zero trt ×year interaction for TSW, or else based on the related significant P-value. Different letters indicate significant differences at P= 0.05 within a factor and parameter.

5.4.2. Effect of N rate strategies (defoliated and non-defoliated) on seed yield

To determine Nopt, defoliated and non-defoliated fertilized and zero-N treatments were regressed for their produced yield as a responsive variate against N rates using lin+expo curves for each year (Figure 5.2-A and B), with the fitted curve parameters given in table 5.4.

The Nopt in 2019 and on non-defoliated and defoliated plots, is indicated by 123 kgN/ha and 170 kgN/ha for a maximum yield of 4.42 and 4.44 t/ha, respectively. A difference in N application of 47 kgN/ha was measured in 2019 (Figure 5.2-A).

In Figure 5.2-B related to 2020, Nopts did not differ between defoliated and non-defoliated crops with values of 206 and 208 kgN/ha, respectively. However, the achieved yield on non-defoliated crops was 5.45 t/ha, whereas defoliated crops only reached 4.96 t/ha of yield. The yield showed almost 0.5 t/ha difference for defoliated plants as a parallel curve to the non-defoliated ones in this specific year.



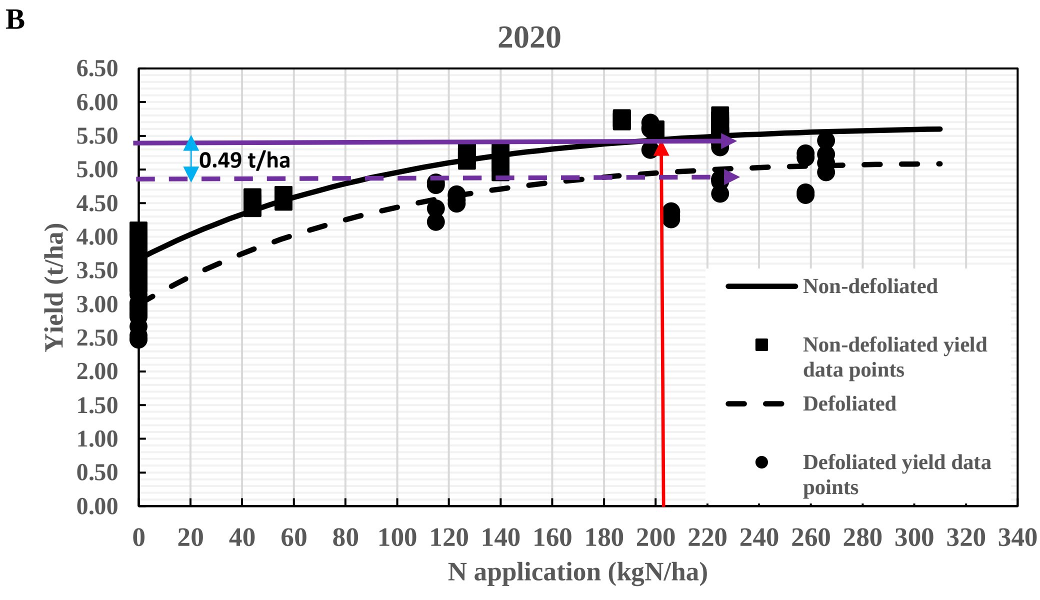


Figure 5.2- A and B: Best Fitted lin+expo on 2019 (Figure A) and 2020 (Figure B) data, for a comparison between defoliated (Rm) and non-defoliated fertilized and unfertilized plots with their defined optimum N rate (red arrows); and maximum yield (purple arrows- Figure B); and the difference between the lines (blue arrows) - Dashed arrows related to defoliated plots.

Table 5.4. The effect of year and defoliation on the best fitted linear + exponential parameters, using multiple linear regression. Yield and N rate were fitted as the function of $Y=A+BR^N+CN$. Economical maximum yield at Nopt is calculated, R^2 is the proportion of variance accounted for, P-value of each equation selected by the stepwise regression; S.E. is the standard error of the observation, df shows the degree of freedom

Site-year	Defoliation	Curve parameters				Nopt	Max. yield at Nopt	R^2	P-value	S.E. (df)
		R	A	B	C	(kg/ha)	(t/ha)			
Year 2019	Defoliated	0.997	12.4	-9.23	-0.013	170	4.44	0.78	0.03	0.255 (92)
	Non-defoliated		18.9	-15.6	-0.028	123	4.42			
Year 2020	Defoliated	0.990	5.58	-2.58	-0.0011	206	4.96	0.91	<001	0.285 (103)
	Non-defoliated		5.91	-2.24	-0.00059	208	5.45			

5.5. Discussion

Early season GAI was significantly reduced following defoliation practice in both years; in 2019, zero-Rm and zero-Rt GAI values were 44% of the non-defoliated treatment whereas in 2020, they had just 31% of the GAI of the uncut plants. The defoliation practice reduced crop N content differently between the two years due to variations that the mechanical mowing practice could cause, which itself was dependant on field soil conditions in January. An unequal crop N reduction of 27% and 51% of zero-Non was reported for zero-Rt and Rm practice, respectively. However, when adding SMN, for calculating early spring SNS, zero-Rm in both years measured similarly, because SMN was a higher value in year 2020.

Harvest N uptake in zero-Non had the highest value in both years with 103 kgN/ha and 96.2 in 2019 and 2020 respectively. It was expected that zero-Rt for both years would return some recycled N to the crop, and would show similar or higher harvest N values to zero-Non. However, this only happened in 2020, where zero-Non harvest N was insignificantly different from zero-Rt. This indicates that the level of N that is successfully recycled into crop N differs with site and year. Therefore, it was not clear if defoliated crops with removed materials would generally uptake higher final N uptake comparing to the situation where plant residuals (as an organic source) would remain on the plots. If this organic source is decomposed, the scavenged N is mineralized and becomes available in the soil, but if mineralized N cannot be synchronized with plant N demand, it can be lost through multiple pathways, such as leaching, denitrification, and ammonia volatilization based on site-year, soil, and weather conditions (Robertson and Vitousek, 2009). Plant residues are only one potential source of many organic materials, which similarly did not become available to the crop. Other source of variations such as, previous crop N, the possibility of an imbalanced C:N, N leaching loss or gaseous loss over growing season are items to notice making harvest N uptake different for zero-N treatments.

Similar studies on mowed crops for different group of crops and climate have shown that the ability of the plant to take up N from organic pools depends on a proper synchronization between plant and microorganisms competing for the same source of N. Depending on decomposition rate and N release from decomposed materials, the N uptake can be different. Nitrogen release during decomposition can contribute little from mowed perennial ryegrass but the ^{15}N labelling showed most of N has been recovered in the soil (Brunetto *et al.*, 2011; Chen *et al.*, 2014). Also when considering Brassica as cover crops, N availability is concluded to vary between regions, as the processes involved in N losses from soil and plant residue are mainly influence by soil and climate conditions, therefore N accumulation in this specific crop differed considerably (Li, 2000; Di and Cameron, 2002; Li et al., 2006).

Excess rainfall occurred in November and December of 2018 with respectively 160 and 130 mm of precipitation and 10˚C temperature; both temperature and rainfall were above the 30-years LTA. It is possible that net N mineralization could well be happened during a humid condition of far below the LTA rainfall and above average temperature in January and February, yet, it could be lost through leaching and made the values numerically more distinctive. The wet-dry weather pattern occurred on each two-month intervals until 2019 harvest time. In 2020, except a considerable rain precipitation of 170 mm in only February, other months, up to harvest, had <60 mm of rainfall with a rising temperature of 6 to 16˚ C, therefore, perhaps a different N-cycle process had happened.

There was no considerable difference among zero-N yield results when interacted with year, as yield components can have a compensatory effect when yield is relatively low (Lardon and Triboi-Blondel, 1995). In 2019, yield was mainly reflected in individual seed weight, as consequently, TSW (g) was significantly higher in this specific year, also in 2019 pod number was significantly higher by 400/m^2 compared to 2020. In 2020, more seeds per pod and therefore, longer pods instead of a massive pod canopy substituted for the lighter weight of individual seed in this year. Higher yield was produced with more seeds/pod in 2020.

A shorter period for seed development, results in less seed number/m^2 as observed on soybean, wheat and barley (Kantolic and Slafer, 2001; Meckel *et al.*, 1984) and also on WOSR (Stafford, 1996). A monthly temperature with higher than LTA from GS 30 onwards, with considerable lower precipitation (below LTA) assembly resulted in milder conditions with a longer pod development in 2020. Assimilating the production of pod hulls which is mainly under the influence of temperature during seed development and seed growth was discussed in some studies (i.e. Mogensen *et al.* 1997).

From observations in these trials, fertilized defoliated crops produced more branches with early leaves formation growing from the callus resulting from damage inflicted by the mower (Appendix 2). Similar to Spink's (1992) observation, shorter pod formation was associated with lower branches, as the crop had a thick green short, late developing canopy. Hence, this could explain the yield difference between defoliated and non-defoliated crops. Leaf removal during flowering GS was shown to impact negatively on yield as there was a reduction in total crop N content, harvest index and seed number per unit area (Ulas *et al.*, 2015).

One possible factor which may impact on the pattern of N uptake is the maximum yield potential, as this factor tends to act as a scaling factor (Sylvester-Bradley, 1992), mainly because seeds (as the sink variable) is a more controlling factor and dominant over source photosynthesis organs. In this study, a useful way of assessing the practical impact of defoliation on N dynamics for a comparison affecting the SNS, harvest N uptake, and subsequent Nopt.

To determine if winter leaf removal result in yield reduction or increasing Nopt, yield and N rates were regressed. In 2019, defoliated-fertilized crops required almost 50 kgN/ha more N to achieve a maximum economical yields of 4.42 t/ha. Notably, in 2020, defoliated crops with similar Nopt of 206 kgN/ha had a yield reduction of 0.5 t/ha, and the curves appeared as parallel lines. Based on UK- canopy management principles it is expected that a crop yielding 0.5 t/ha less, there is a need for an additional 30 kg/ha of N fertilizer (Berry *et al.*, 2011). Interestingly, the difference of defoliated and zero-Non in this year also was calculated as 0.66 t/ha using the model parameters. Although it is not shown here, theoretically it is suggested to consider 30 kg/ha higher N on defoliated crops.

To understand the effect of removing 1 kgN/ha of canopy in the spring on the requirement for more fertilizer N, the difference between SNS for zero-Non and zero-Rm treatments were calculated. In 2019, this value was 15.8 kgN/ha, on the other hand, the yield difference for the two different Nopts in this year was 47 kgN/ha, hence, for each 1 kgN/ha of lost vegetation in spring, approximately 3 kgN/ha is needed for the yield compensation.

Winter defoliation has not been studied in mild climate of Ireland on WOSR, where the defoliation effect on yield and N rates as pigeon damage was always a question. However, the issue has been known and reported on since 1969 when a UK report indicated that 36% of farmers in England and Wales had pigeon damage problem. This value increased to 43% in 1975 (Fletcher, 1976), and was listed as a dominant issue according to a survey by Lane (1983) with an average of 69% of oilseed rape farms being defoliated in Britain. Tatchell (1977), also considered woodpigeon (*Columba palumbus*), as a vertebrate pest of winter oilseed rape during 'early stages of crop development' in the UK climate. In one comprehensive study by Inglis *et al.*, (1989), pigeon damage and mechanical defoliation were studied in 508 ha in central and southern England. It was shown that the damage was negligible during December, but then increased during January, February and March before April. Results of the study showed on average a 9% of yield reduction was observed due to pigeon attack, and more economical problems due to uneven ripening time and lower oil content from damaged crops were issues reported from the survey during 1978 to 1981. In the same study, crops were hand removed at various growth stages, leading to similar results with negligible effect on yield from defoliation damage in December and April, due to a reduction of pod formation at harvest and uneven ripening, lower plant density at harvest for smaller seed number per plant. The pigeon damage was notified as an economically important issue, which needed intense scaring campaigns throughout the period from mid-January to the end of March. Aligned with the older studies from the 70s, this study also showed that if defoliation occurs during wintertime, an additional N application is required of about 30-50 kgN/ha, depending on the severity of pigeon damage. Notably it is not practically easy to imitate pigeon damage by mechanical defoliation. Thus, depending on how even the seeding is applied, patchiness of the field, the severity of pigeon damage can be different (Forristal, P.D, Oral communication, Teagasc Open Day, June 2020).

It was shown that, depending on winter vegetation loss in January, final N uptake compensated for the vegetation loss on zero plots with no difference between removed or retained defoliated materials. Additional available N through different sources of mineralization, which synchronized with plant N demand and soil N availability, was efficient therefore; yield was indifferent due to compensatory effect shown as yield components. However, this condition was different on fertilized defoliated crops based on site-year, possibly, soil moisture deficit (SMD) changeably occurred over growing season when there was an external source of N through mineralization. This would require a more detailed measurement on a site-year basis, because defoliation compensatory potential could be different when N fertilizer is applied. Retained mowed materials also on unfertilized plots, did not contribute N for a beneficial harvest N uptake during the growing season.

5.6. Conclusion

This study compared early spring SNS, harvest N uptake and N use efficiencies, yield and its components on unfertilized defoliated (zero-Rm and zero-Rt) and non-defoliated (zero-Non) crops. Spring SNS differed significantly between zero-Non and zero-Rm, but final N uptake differences varied by site-year. It was shown that plant residuals from zero-Rt crops did not necessarily recycle back to the defoliated crops, as there was no meaningful difference between zero-Rt and zero-Rm across years. Possible assumed reasons are mainly attributed to the slow decomposition, or mineralization and different timing of the synchronization between N availability and the crop N demands. Yield and yield components did not differ, although N utilization was most efficient in zero-Rm crops.

With fertilized crops, yield was regressed with N rates on defoliated and non-defoliated to define the optimum application rate based on the maximum economical N rate. Results differed between the two years in terms of yield potentials; in 2019, yield was at 4.4 t/ha, and an extra fertilizer N amount of 47 kgN/ha was needed to meet the gap between defoliated and non-defoliated crops. In 2020, due to better canopy management or less SMD, yield potential was differently higher by 4.9 t/ha (for defoliated) and 5.4 t/ha (for non-defoliated) t/ha for a similar Nopt. Therefore, additional fertilizer N application was needed for compensating the yield loss.

6.0. Overall Discussion

In this chapter, the overall findings of the three research chapters (3 to 5) are considered together in the context of evaluating and developing a Canopy Management (CM) system suitable for a range of post-winter crop sizes for a milder climate.

In Chapter 3, soil mineral N uptake efficiency (SNUpE) on unfertilized crops and fertilizer N uptake efficiency (FNUpE) at various N rates were measured and compared to studies from the UK and continental European climates (Germany and France). Specifically, the intention was to test if crop N uptake and SMN over winter equated to the final N uptake at harvest on unfertilized plots. Also the impact of SD and site-year were assessed on FNUpE values to demonstrate any similarities to the standard UK value of 60%.

The research reported in Chapter 4 included the testing of two key elements of the UK-CM approach practiced in the UK. The crop N content per unit of canopy size (GAI) was quantified at various growth stages and SDs. To predict the optimum canopy size, the GAI measurements were regressed against fractional interception at flowering, and also once more against harvest seed yield.

In Chapter 5 the experiment was extended by studying a defoliation practice on early sowing dates, as an alternative for producing various canopy sizes and explore the impact of factors that defoliate WOSR (such as pigeon grazing). Unfertilized crops were subjected to mowing practices during two winters, where plant residuals were either removed (zero-Rm) or retained (zero-Rt), and were compared to non-defoliated crops. Also in Chapter 5, to determine the Nopt for fertilized and unfertilized crops, defoliated (removed materials) and non-defoliated crops were regressed for their N rates and yields. Then, key findings were gathered to understand whether a mild Atlantic climate affected the key principles underpinning the canopy management system from the UK or whether some adjustments were needed.

SNUpE varied among the three sowing dates Earlier SDs, SD1 and SD2, had SNS to harvest N uptake ratios of only slightly higher than 1 with, 1.13 and 1.14; however, the SD3 crops (late sowing date) had much higher uptake efficiency of 1.68. The smaller denominator in the equation mainly explained higher efficiency values ($\frac{Final\ N\ uptake}{Spring\ SNS}$). Additionally available soil N, released through mineralization, estimated by subtracting final N uptake and spring SNS with 10 to 12 kgN/ha for SD1 and SD2, comparing to 38.4 kgN/ha on SD3 crops. Greater supply of N on later sown crops may reflect a higher volume of mineralized N being available to the plant due to a better synchronization between plant N demand and N availability (Robertson and Vitousek, 2009). Therefore, due to the scavenging nature of the late sown crops and favourable soil moisture and temperature (Laine *et al*., 1994; Macduff *et al.*, 1987), these crops had more N uptake than expected from the SNS values. Hence, AAN appeared later and higher than for SD1 and 2. This potential AAN might well be taken up earlier, or missed out, as the result of run-off, leaching, immobilization or denitrification, on earlier SDs. Generally, SNS and crop N uptake are influenced by soil organic matter, C:N ratio and the influence of soil textures on soil temperature and moisture retention. Studies on AAN release on grasslands in Ireland have shown very high values with a background N availability of 112 kg/ha/year recorded by Humphreys, (2007) on a grassland site adjacent to the location of the research in this thesis. Also, values of 139 kg/ha/year on different (south eastern) sites were reported by Humphreys (2007). The highest amount of N availability was associated with high soil temperature coinciding with adequate soil water availability. The lowest N release is in winter during cold soil conditions and waterlogging. Some AAN can be released between late October and the middle of March with a value of 43 kgN/ha (=270 gN/ ha/ day) at Moorepark (County Cork, Ireland) (Humphreys, 2007). There were also reports of N release during winter months between 200 and 250 gN/ha/day during November, December, and January (O'Donovan *et al.*, 2004). Overall, there is evidence to suggest the likelihood of higher background N (or AAN) release in milder climates. Soil N supply is difficult to measure and predict and it has been expressed as the “black box”(Grzebisz *et al.*, 2018) of the soil, with many factors and relationships contributing to N supply that are poorly understood.

The availability of a measurement system for AAN would help produce more precise N fertilizer recommendations. Some laboratories estimate AAN using an anaerobic soil test incubated for 7 days at 40 ˚C for measuring all potential mineralizable ammonium between mid-January to March (Blake-Kalff and Blake, 2014), but the utility of these systems in different soils and climates remains to be determined. The development of improved measurement or prediction of AAN would allow more precise determination of fertilizer N needs in a mild climate with consequent benefits for crop production efficiency and less environmental risk.

In UK research, spring SNS (as an explanatory variant) was regressed against harvest N uptake (responsive variant) in a study by Kindred *et al.* (2012). The authors discovered where there was a 1:1 ratio of spring SNS and final N uptake, a statistically significant model with positive linear slopes and intercepts was produced. The intercept predicts the deposition (AAN) and the slope predicts mineralisation and the recovery of SMN. In this study, however, no such direct regression could be found due to spatial- temporal variations in sampling. For example, samples were taken at different points within a plot whereas the dynamic soil N characteristics remained unknown, and this was also discussed in the UK study.

A considerable amount of the N in the available soil nitrogen pool can be recycled a number of times throughout the growing season before it enters the mineralisation/immobilisation turnover cycle (Hatch *et al.*, 2000). Hence, there is a complexity of quantifying soil N values into an N prediction system. Studies from different countries within continental European (Germany, France, Netherlands, Denmark) and an Atlantic-continental country (UK) on WOSR and N supply have shown that using spring SNS (with a focus on SMN) is not “satisfactory” (Łukowiak and Grzebisz, 2020). In the UK-CM system, SNUpE is assumed as 100% to allow for a relatively simple N prediction system which was initially developed from managing wheat crops (Kindred and Sylvester-Bradley, 2014; Sylvester-Bradley *et al.*, 1998). Despite the modest variations from 100% efficiency of SNUpE, earlier SDs seemed to have the closest values to the assumption. However, for late sowing dates it seems likely that the recommendation system must account for a larger efficiency of SNUpE than 100% and AAN should be estimated.

In continental European studies, for calculating SNS, autumn canopy N + SMN was shown to be a more reliable indicator for adjusting optimum N fertilizer rate than spring canopy N+SMN (Henke *et al.*, 2009). Soil N availability in spring is less, due to low soil temperature, little mineralisation over winter, and nitrate leaching (Sieling *et al.*, 1999). In contrast to continental studies, the efficiency of soil N uptake in regions with milder winters is likely to be higher due to insignificant leaf loss or higher rate/ frequency of mineralization.

FNUpE had a range from 27.3% to 69.0% across site-years, SDs and N strategies. Similarly, in Berry and Spink (2009) study, FNUpE ranged from 23% to 63%, as N application decreased also FNUpE was more efficient on earlier sown crops, due to the fact that early (August) sown crops can rapidly reach stem elongation as nitrate uptake increases (Malagoli *et al.*, 2005; Sieling *et al.*, 2017). In site-year 1 and 2 of this study, higher precipitation (compared to LTA) in March and April, when fertilizer N was applied, resulted in significantly lower values of N application efficiency. In site-year 3, less precipitation occurred around the timing of N application where FNUpE had considerably higher values. Additionally, including a lower N application strategy (CMLo) resulted in higher FNUpE values in site-year 3 and 2. Average values for the two site-years were 53.6%, 57.3%, and 48.2% respectively for SD1, SD2, SD3 among which SD3 had the smallest value. It is possible that, SD3 crops were not able to capture fertilizer N efficiently, while instead N uptake from soil was shown to be highly synchronized with the late sown crop`s N demand.

For future research, a more specific crop and soil N principles should be examined, as suggested by Schepers and Meisinger, (1994). This can be seen as a stored N source, which may contribute to SNS but is often not measured in the N content of the roots. Root N content was measured as a function of days-after-sowing dates; with a maximum value of 20 kgN/ha (Gabrielle *et al.,* 1998). In N deficient crops (such as zero-N plots), photosynthesis can distribute proportionately more to the roots, resulting in mineralization being underestimated if only aboveground biomass N content is taken into account (Schepers and Meisinger, 1994). In French N management systems, N uptake is estimated in the whole of the plant, including roots, at the beginning of winter in cold eastern parts, and at the end of winter for all regions in the country. Then, if plant N at the end of winter is calculated to be equal or greater at the beginning of winter, crop N will be estimated similarly as the value of the end of winter. However, if crop N is smaller by the end of winter, then it is assumed that 50% of the lost N is recycled and available for subsequent plant uptake (Champolivier, L., Email communication with Terres Inovia, April 2020). Another noticeable principle is considering leaching loss on unfertilized plots. In this study, it was assumed leaching loss would be small, as the crop is growing under N limiting conditions. Denitrification from zero-N plots is often ignored in studies, as there is insignificant NO_3 around root zones during the growing season. However, it has been suggested as the most common N loss mechanism happening on Irish grassland (Humphreys, 2007). Volatile N losses from living plant tissues has also been assumed to be insignificant and this contributes to an underestimation of mineralization (Schepers and Meisinger, 1994).

In chapter 4, the N demand that the OSR plants require for an optimum canopy size to intercept maximum radiation at flowering for later formation of biomass and yield was determined. An approximate value of 50 kgN/ha/GAI was used as the basis of the UK canopy management system (Berry and Spink 2009). In this study, the average value across years among

SDs was 54.10 (±2.46 as S.E.M) kgN/ha/GAI across site-years from the slope of the linear regression. A slightly different value of 53.40 kgN/ha/GAI measured for different GSs.

Regression between the fraction of light interception (FI) and GAI was based on Beer-Lambert`s law, where the range of GAI corresponding to 95% of FI, is defined as the economical optimum range. Depending on site-year, N application rates and SD, the extinction coefficients (k) were different. A single exponential fitted curve for all sowing dates, which followed Beer-Lambert`s law, adequately described the GAI-FI relationship in each of the three years.

To define an economical range where an optimum GAI can be achieved when regressed with the 95% maximum FI, a 0.95 confidence interval (CI) with its lower and upper limits was used in an attempt to recommend a higher level of precision as a GAI target to farmers. Compared to 3.00 to 4.00 being considered the optimum GAI in UK studies (Lunn *et al*., 2001), FI at 95% of maximum radiation showed an average range of [3.54, 4.05], although there was a wider range due to SD3 with 4.18, 4.66 and 4.50, respectively for the upper limits of year 1, year2 and year3.

In addition, when GAI was regressed with seed yield (t/ha) in year 1, a GAI of 4.20 units was the optimum value where the maximum yield was 5.41 t/ha, using linear plus exponential curves. In site-year 2 with better spring growth conditions, a lower GAI value of 3.39 (but a wide range of 0.95 CI [2.56 to 4.21]) showed an optimum canopy size with a maximum yield of 5.15 t/ha.

As site- year 3 consisted of a quite late SD3 (September, 19th to 21st) a significant SD effect was noted with parallel fitted curves for the GAI with yield. Linear plus exponential curves from GAI and yield defined optimum GAI values of 3.08, 3.60 and 5.06 respectively on SD1, SD2 and SD3 for maximum yields of 5.37, 5.57 and 4.58 t/ha respectively in site-year3. Therefore, the target GAI in this study on early SDs across all years was shown to have a range from

3 to 4.5 unit, whereas this value can be as high as 5.06 (site-year 3/ SD3: GAI and yield regression). Hence, a wider range within the 0.95 confidence interval was calculated compared to the UK values. This difference can be attributed to the higher yield potential that WOSR crops has shown comparing to the yield assumption of 3.5 t/ha obtaining from optimum GAI value from UK-CM studies.

Based on the measured values across site-years and different experiments, it is possible to generate Irish canopy management principles, for which the target optimum GAI was larger than the UK, FNUpE% smaller, and N uptake/unit of GAI was slightly higher than 50 on early SDs. The UK-CM from equation 6.1 was used to determine the required fertilizer N rates on three different SD categories: Mid to end August categorized as SD1 and SD2, and end of September as SD3 showing measured values of CM principles (Table 6.1.).

Fertilizer N Requirement based on CM (kg N/ha)

$$= \frac{\textbf{Crop N demand } (\textbf{GAI} \times \textbf{N uptake per GAI at flowering}) - \textbf{Spring Soil Nitrogen Supply } (\textbf{SMN} + \textbf{Crop N})}{\textbf{Fertilizer N uptake efficiency } \%}$$

(E.q. 6.1)

Table 6.1. Measured canopy management (CM) principles in Irish conditions of this study

Sowing dates	Measured CM principles					AAN (kgN/ha)
	Target GAI	N uptake/GAI (kgN/ha)	Crop N demand (kgN/ha)	FNUpE%	SNUpE	
Mid-Aug to end Aug	3.7	54.3	201	55%	1.13	11.4
Mid-Sept	4.4	45.7	201	48%	1.68	38.4
Available Reference	Average values from tables 4.4. and 4.6. across years	Average from Table 4.3. at flowering stage	GAI × N uptake/GAI	Average values from Table 3.6.	Average values from Table 3.3.	Chapter 3 calculations

The main point is to test Irish CM measured principles against the measured Nopt, separated at various SD and year interactions (Table 6.2.). Calculated values showed that N values from Irish principles are estimating higher values (i.e. year 2), but considerably different mainly for SD3.

Canopy management principles were able to be adjusted better for early SDs. When comparing average values of required fertilizer N for SD1 and SD2, year 1 CM values were well correspondent to the measured Nopt, year 2 showed 53 kgN/ha higher value than the maximum economical yield and year 3 was only different by 9 kgN/ha to get to the Nopt.

The difference between Nopt and measured N from the principles on SD3, was consistently higher in year 2 and year 3 by 53 and 58 kgN/ha. Hence, this shows the Irish principles could be better adjusted on early SDs as they are closer to Nopt values; however, principles might overestimate approximately up to 60 kgN/ha on the late SDs (based on two years data).

Table 6.2. A comparison between required fertilizer N using values from table 6.1. and the measured Nopt at different SD×years

Site-years	Sowing Dates	Measured SNS Ref: Table 3.3.	SNS × SNUpE*	Required N fertilizer based on Irish CM principles**	Measured Nopt	Max. economical Yield*** (t/ha)
		(kgN/ha)				
Year 1	**SD1**	142	160	74	113	4.91
	SD2	104	118	152	.	.
	SD3	67.6	114	182	.	.
Year 2	**SD1**	76.6	87	208	143	4.37
	SD2	87.9	99	185	143	
	SD3	63.6	107	196	143	
Year 3	**SD1**	86.8	98	187	190	5.63
	SD2	93	105	174	190	5.69
	SD3	48.8	82	248	190	4.06

***To measure the exact amount of SNS, average SNUpE of 1.13 was used on SD1 and SD2 and 1.68 on SD3 across site-years. **using the equation 6.1. and values from table 6.1. ***Values from table 3.5.**

Results based on site-year 3 with different Nopt values and Max. yield points, showed the difference between predicted values and Nopt becomes larger as SD delays; simultaneously, yield was reduced considerably in site-year3 /SD3. Notably, this SD in that specific site-year was delayed until 20th September. As obviously, it is not possible to forecast long-term weather conditions, it can be recommended that a sowing date of at-most in the first half of September would perhaps reduce the difference between predicted values and the Nopt for avoiding yield loss, and excess fertilizer N applications.

Moreover, the pool of potential mineralizable N should be considered as a dynamic unstable value, changes based soil and weather conditions. A better synchronization has occurred making the prediction easier. Whereas, AAN released for the latest sown crops made the measurements more challenging to confirm CM principles for this SD.

In Chapter 5, for further understanding of the impact of winter defoliation on crop development and subsequent N requirement, mid-winter crop defoliation was studied through mowing, but because late sown crops had a small canopy with little scope for defoliation, this chapter only considered SD1 and SD2 as one data set for further analysis. Unfertilized plots were defoliated with two cutting strategies: one with the cut plant residues retained on the plot (zero-Rt) and another removing defoliated plant material from the plots (zero-Rm). The effect of defoliation on final (harvest) N uptake was affected by season and by whether the defoliated material was removed or retained. Harvest N uptake in the non-defoliated, unfertilized plots (zero-Non) was higher than zero-Rt in 2019 and higher than zero-Rm in 2020, indicating that differences were seasonal dependent. Risk of N loss from the system where defoliation was practised or slower rate of mineralization and lack of synchronization between plant N demand and soil N availability could perhaps be some notable reasons from many spatial-temporal variations, which perhaps has occurred. Therefore, it was not necessarily possible to assert if defoliated crop material remaining on the plot would be decomposed and recycled back to the plant before the end of growing season.

Little or no differences in NUE or NUtE was observed among zero-N defoliated and non-defoliated crops. The non-defoliated treatment yielded more than one of the defoliated treatment in each of the two years.

In this work, it was also sought to determine whether the fertilizer N response differed between defoliated and non-defoliated crops (on zero-Rm only). In year 2019, when N rates were regressed against yield for fertilized, defoliated-Rm and non-defoliated plots, an approximately 50 kg/ha more N was needed for defoliated crops in order to obtain similar maximum yield to non-defoliated plots. Based on what was obtained from 2019 on yield and N rate, depending on the sit-year, there was a possibility of compensation for yield. If one kg of N loss happens in winter, a 3 kg/ha extra N is needed through application of fertilizer N, for similar site-year conditions as 2019.

In year 3, however, the Nopt was similar for non-defoliated and defoliated crops, yet the defoliated crops yielded 0.5 t/ha less and based on the UK-CM theory, an amount of 30 kg N/ha could be suggested to compensate for the yield loss.

The benefits of reducing the N application has been discussed before, with the aim of N fertilizer application reduction based on the canopy size at flowering. There was an insignificantly different seed yield between the N rate allowed by the current N determining system: (225kgN/ha for soils at N index 1) compared to many of the canopy management systems evaluated here, which recommended lower N application rates. This resulted in N reductions to improve profitability and reduce leaching risk. These results were transferred to Teagasc crop advisors on a year basis and to the stakeholders in the final project year 2020-2021. The UK N strategy principles, which were tested in this project, can largely be applied with confidence and there may be future scope for further N reductions if AAN could be accurately predicted. Based on statistics from Teagasc crop report, harvest report, 2021, WOSR area has increased by 16% from 8,749 ha in 2020 to 10,102 ha in 2021. In addition, crop yield has been consistent over the last 5 years when CM principals have been tentatively deployed.

7.0. Overall Conclusion

Overall, while the principals of canopy management systems, such as that derived in the UK, appeared with differences in a milder and wetter climate, varied from season to season. These may result in different crop management and fertilizer advice, but they also indicate where future research is required to be more precise in Irish fertilizer N application. Specific conclusions include:

i. Optimum canopy size at flowering for early sowing dates was 3.50 to 4.50 GAI units. Later sown crops produced a higher GAI value at flowering, with values of up to5 being optimum in these crops.

ii. Each unit of GAI includes approximately 53.4 kgN/ha

iii. As the result of (i) and (ii), crop N demand based on canopy requirements at flowering, is predicted to be 187 to 240 kgN/ha (optimum canopy size × crop N uptake each GAI unit). Also for late sown crops, this can reach 267 kgN/ha/GAI at a maximum level.

iv. Soil NUpE was slightly a higher value; about 1.13, 1.14 for SD1 and 2, and 1.68 for SD3; hence, it is not quite following the 1:1 ratio of final N uptake to spring SNS assumed in UK canopy management calculations.

    The additional available N released through the growing season, resulted in contribution of more canopy and yield formation. This value was higher in SD3.

v. Fertilizer NUpE% varied considerably depending on N application rates, sowing date and site-years. It was most relevant to measure FNUpE at the optimum N rate (separated by SD and site-years) for comparisons with the UK assumed value of 60%. Based on three years data, together on SD1 and SD2 the average value was calculated as 55.0% and 48.6% for SD3.

vi. Defoliation over winter and on unfertilized crops had different impact on harvest N uptake based on vegetation loss, or site-year soil and weather conditions. Regressions of yield and N rates between fertilized and unfertilized (defoliated and non-defoliated) showed higher N application is required for defoliated crops to achieve the maximum economical yield. Based on one site-year data (2019), it was shown that each 1 kgN/ha of vegetation loss in early spring needed 3 kg/ha of fertilizer N uptake to avoid yield loss.

8.0 Bibliography

Adhikari, C., Bronson, K., Panuallah, G., Regmi, A., Saha, P., Dobermann, A., Olk, D., Hobbs, P. and Pasuquin, E. (1999) 'On-farm soil N supply and N nutrition in the rice–wheat system of Nepal and Bangladesh', Field Crops Research, 64(3), pp. 273-286.

AHDB Nutrient Management Guide (RB209). Available online (www. AHDB.org.uk)

Appel, T. (1994) 'Relevance of soil N mineralization, total N demand of crops and efficiency of applied N for fertilizer recommendations for cereals—Theory and application', Zeitschrift für Pflanzenernährung und Bodenkunde, 157(6), pp. 407-414.

Alboresi A, Gestin C, Leydecker MT, Bedu M, Meyer C, Truong HN. (2005) 'Nitrate, a signal relieving seed dormancy in Arabidopsis'. Plant, Cell & Environment 28, 500–512.

Alexander, I. J. (1983) 'The significance of ectomycorrhizas in the nitrogen cycle'. *In* "Nitrogen as an Ecological Factor" (J. A. Lee, S. McNeill and I. H. Rorison, eds.), pp. 69-93. Blackwell Scientific Publishing, Oxford.

Allen, E. J., and Morgan, D. G. (1972) 'A quantitative analysis of the effects of nitrogen on the growth, development and yield of oilseed rape'. J. Agric. Sci. 78, 315–324.

Ammeter, A., So, K. and Duncan, R.W. (2021) 'Analysis of cruciferin content in whole seeds of *Brassica napus* L. by near-infrared spectroscopy'. Journal of the American Oil Chemists' Society.

Andersen, M.N., Heidmann, T. and Plauborg, F. (1996) 'The effects of drought and nitrogen on light interception, growth and yield of winter oilseed rape'. Acta Agriculturae Scandinavica B-Plant Soil Sciences, 46(1), pp.55-67.

Anonymous (1996) 'Calcul de la fertilisation azotee de cultures annuelles'. Available Online https://side.developpement-durable.gouv.fr/GUAD/doc/SYRACUSE/80872.

Aubertot J.N., Pinochet X., Doré T. (2004) 'The effects of sowing date and nitrogen availability during vegetative stages on *Leptosphaeria maculans* development on winter oilseed rape'. Crop protection, 23/7, 635-645.

Aufhammer, W., Kubler, E. and Bury, M. (1994) 'Stickstoffaufnahme und Stickstoffrückstände von Hauptfrucht-und Ausfallrapsbeständen', Journal of agronomy and crop science, 172(4), pp. 255-264.

Balodis, O., Gaile, Z. and Strikauska, S. 'Changes in sugar content of winter oilseed rape plant during winter'. Annual 18th International Scientific Conference" Research for Rural Development," Jelgava, Latvia, 16-18 May 2012. Volume 1: Latvia University of Agriculture, 24-30.

Barraclough, P. (1989) 'Root growth, macro-nutrient uptake dynamics and soil fertility requirements of a high-yielding winter oilseed rape crop', Plant and Soil, 119(1), pp. 59-70.

Behrens, T. (2002) Stickstoffeffizienz von Winterraps (*Brassica napus* L.) in Abhängigkeit von der Sorte sowie einer in Menge, Zeit und Form variierten Stickstoffdüngung. Cuvillier Verlag.

Behrens, T., Ulas, A., Wiesler, F. and Horst, W. J. (2011) 'Agronomic traits contributing to nitrogen efficiency of winter oilseed rape cultivars', Field Crops Research, 124(1), pp. 114-123.

Beres, J., Becka, D., Tomasek, J. and Vasak, J. (2019) 'Effect of autumn nitrogen fertilization on winter oilseed rape growth and yield parameters'. Plant, Soil and Environment, 65(9), pp.435-441.

Berry, P., Teakle, G., Foulkes, J., White, P. and Spink, J. 'Breeding for improved nitrogen use efficiency in oilseed rape'. V International Symposium on Brassicas and XVI International Crucifer Genetics Workshop, Brassica 2008 867, 97-102.

Berry, P. and Spink, J. (2006) 'A physiological analysis of oilseed rape yields: past and future', The Journal of Agricultural Science, 144(5), pp. 381-392.

Berry, P. and Spink, J. (2009a) 'Understanding the effect of a triazole with anti-gibberellin activity on the growth and yield of oilseed rape (*Brassica napus*)', The Journal of Agricultural Science, 147(3), pp. 273-285.

Berry, P. M. and Spink, J. H. (2009b) 'Canopy Management' and Late Nitrogen Applications to Improve Yield of Oilseed Rape. p.32, HGCA: London.

Berry, P., Kindred, D., Olesen, J. E., Jorgensen, L. and Paveley, N. (2010a) 'Quantifying the effect of interactions between disease control, nitrogen supply and land use change on the greenhouse gas emissions associated with wheat production', Plant Pathology, 59(4), pp. 753-763.

Berry, P., Spink, J., Foulkes, M. and White, P. (2010b) 'The physiological basis of genotypic differences in nitrogen use efficiency in oilseed rape (Brassica napus L.)', Field Crops Research, 119(2-3), pp. 365-373.

Berry, P., Roques, S. and Clarke, S. (2011) 'Predicting the optimum rate and timing of nitrogen fertiliser for winter oilseed rape'. 13th International Rapeseed Congress, Prague, pp. 5-9.

Billen, G., Garnier, J. and Lassaletta, L. (2013) 'The nitrogen cascade from agricultural soils to the sea: modelling nitrogen transfers at regional watershed and global scales', Philosophical Transactions of the Royal Society B: Biological Sciences, 368(1621), pp. 20130123.

Bilsborrow, P., Evans, E. and Zhao, F. (1993) 'The influence of spring nitrogen on yield, yield components and glucosinolate content of autumn-sown oilseed rape (Brassica napus)', The Journal of Agricultural Science, 120(2), pp. 219-224.

Blake-Kalff, M. M. and Blake, L. (2014) 'Assessment and prediction of nitrogen mineralisation and its effect on crop productivity'. In: Proceedings-International Fertiliser Society, 754, International Fertiliser Society, Cambridge: UK, 1-20.

Blum, A. (2005) 'Drought resistance, water-use efficiency, and yield potential—are they compatible, dissonant, or mutually exclusive?' Australian Journal of Agricultural Research, 56(11), pp. 1159-1168.

Booth, E.J., Bingham, I., Sutherland, K.G., Allcroft, D., Roberts, A., Elcock, S. and Turner, J. (2005). 'Evaluation of factors affecting yield improvement in oilseed rape'. HGCA Research Review, 53.

Borzęcka-Walker, M., Faber, A., Pudełko, R., Kozyra, J., Syp, A. and Borek, R. (2011) 'Life cycle assessment (LCA) of crops for energy production', Journal of Food, Agriculture & Environment, 9(3,4), pp. 698-700.

Bouchet, A.S., Nesi, N., Bissuel, C., Bregeon, M., Lariepe, A., Navier, H., Ribiere, N., Orsel, M., Grezes-Besset, B., Renard, M. and Laperche, A. (2014) 'Genetic control of yield and yield components in winter oilseed rape (*Brassica napus* L.) grown under nitrogen limitation'. Euphytica, 199(1), pp.183-205.

Bouchet, A.-S., Laperche, A., Bissuel-Belaygue, C., Snowdon, R., Nesi, N. and Stahl, A. (2016) 'Nitrogen use efficiency in rapeseed. A review', Agronomy for Sustainable Development, 36(2), pp. 38.

Brunetto, G., Ventura, M., Scandellari, F., Ceretta, C. A., Kaminski, J., de Melo, G. W. and Tagliavini, M. (2011) 'Nutrient release during the decomposition of mowed perennial ryegrass and white clover and its contribution to nitrogen nutrition of grapevine', Nutrient Cycling in Agroecosystems, 90 (3), pp. 299-308.

Buckley, C. and Carney, P. (2013) 'The potential to reduce the risk of diffuse pollution from agriculture while improving economic performance at farm level', Environmental science & policy, 25, pp. 118-126.

Cameron, K., Di, H. J. and Moir, J. (2013) 'Nitrogen losses from the soil/plant system: a review', Annals of Applied Biology, 162(2), pp. 145-173.

Campbell, G. S. (1986) 'Extinction coefficients for radiation in plant canopies calculated using an ellipsoidal inclination angle distribution', Agricultural and Forest Meteorology, 36(4), pp. 317-321.

Cassman, K., Dobermann, A., Cruz, P. S., Gines, G., Samson, M., Descalsota, J., Alcantara, J., Dizon, M. and Olk, D. (1996) 'Soil organic matter and the indigenous nitrogen supply of intensive irrigated rice systems in the tropics', Plant and Soil, 182(2), pp. 267-278.

Castro Marín I, Loef I, Bartetzko L, Searle I, Coupland G, Stitt M, Osuna D. (2011) 'Nitrate regulates floral induction in Arabidopsis, acting independently of light, gibberellin and autonomous pathways'. Planta 233, 539–552.

Chen, J. and Black, T. (1992) 'Foliage area and architecture of plant canopies from sunfleck size distributions', Agricultural and Forest Meteorology, 60(3-4), pp. 249-266.

Chen, B., Liu, E., Tian, Q., Yan, C. and Zhang, Y. (2014) 'Soil nitrogen dynamics and crop residues. A review', Agronomy for Sustainable Development, 34(2), pp. 429-442.

Clever, J., Wu, X. and Schull, P. (2015) 'China–Oilseeds and product annual–Record imports and declining production', GAIN Report Number: CH15008, 153.

Conant, R. T., Paustian, K. and Elliott, E. T. (2001) 'Grassland management and conversion into grassland: effects on soil carbon', Ecological applications, 11(2), pp. 343-355.

Coquil, B., Bordes, J. P. and Stafford, J. (2005) 'FARMSTAR: an efficient decision support tool for near real time crop management from satellite images', Precision agriculture, 5, pp. 873-880.

Coulter, B. S. and Lalor, S. (2008) 'Major and Micro Nutrient Advice for Productive Agricultural Crops'. Teagasc Agriculture and Food Development Authority, Johnstown Castle, Wexford: Ireland.

Cramer, N. (1990) 'Oilseed rape, Breeding, cultivation and marketing of oilseed rape'. Raps. Zuechtung, Anbau und Vermarktung von Koernerraps.

Craswell, E. and Godwin, D. (1984) 'The efficiency of nitrogen fertilizers applied to cereals grown in different climates'. CIMMYT, No. REP-3326.

Creamer, R., Simo, I., Reidy, B., Carvalho, J., Fealy, R., Hallett, S., Jones, R., Holden, A., Holden, N. and Hannam, J. (2014) 'Irish Soil Information System-Synthesis Report (2007-S-CD-1-S1)', Wexford: Teagasc. Available online at: http://gis. teagasc. ie/soils/downloads/EPA_RR130_PRINT. pdf.

Cropquest. Oilseed rape/ Crop Research programme. Available Online: www.Teagasc.ie.

Dawson, J. C., Huggins, D. R. and Jones, S. S. (2008) 'Characterizing nitrogen use efficiency in natural and agricultural ecosystems to improve the performance of cereal crops in low-input and organic agricultural systems', Field Crops Research, 107(2), pp. 89-101.

Defra (2010) 'Fertiliser manual RB209. Department for Environment', Food and Rural Affairs, London, UK.

Dejoux, J.-F., Recous, S., Meynard, J.-M., Trinsoutrot, I. and Leterme, P. (2000) 'The fate of nitrogen from winter-frozen rapeseed leaves: mineralization, fluxes to the environment and uptake by rapeseed crop in spring', Plant and Soil, 218(1-2), pp. 257-272.

Dejoux, J.-F., Meynard, J.-M. and Reau, R. (1999) 'Rapeseed new crop management with very early sowing in order to reduce N-leaching and N-fertilization'. New Horizons for an Old Crop. Proc. of the 10th Inter. Rapeseed Congress, GCIRC: CD-RON, Canberra-Australia, 26-29.

Dejoux, J.F., Meynard, J.M., Reau, R., Roche, R. and Saulas, P. (2003) 'Evaluation of environment friendly crop management systems for winter rapeseed based on very early sowing dates.' Agronomie, 23(8), p.12.

De Willigen, P. (1986) 'Supply of soil nitrogen to the plant during the growing season'. In "Fundamental, Ecological and Agricultural Aspects of Nitrogen Metabolism in Higher Plants (H. Lambers, J. J. Neeteson and I. Stulen, eds.), pp. 417-432. Martinus Nijhoff, Dordrecht.

Di, H.J. and Cameron, K.C. (2002) 'The use of a nitrification inhibitor, dicyandiamide (DCD), to decrease nitrate leaching and nitrous oxide emissions in a simulated grazed and irrigated grassland'. Soil use and management, 18(4), pp.395-403.

Diepenbrock W (2000) 'Yield analysis of winter oilseed rape (*Brassica napus* L.) ': a review. Field Crop Res 67:35–49.

Diepenbrock, W. & Grosse, F. (1995) 'Advances in Plant Breeding 17'. Supplements of the Journal Plant Breeding. Beihefte zur Zeitschrift für Pfanzenzü chtung, pp. 2189.

Diepenbrock, W. and Geisler, G. (1979) 'Compositional changes in developing pods and seeds of oilseed rape (Brassica napus L.) as affected by pod position on the plant', Canadian Journal of Plant Science, 59(3), pp. 819-830.

Domsch, K., Beck, T., Anderson, J., Söderström, B., Parkinson, D. and Trolldenier, G. (1979) 'A comparison of methods for soil microbial population and biomass studies', Zeitschrift für Pflanzenernährung und Bodenkunde, 142(3), pp. 520-533.

Dosdall, L.M., Dolinski, M.G., Cowle, N.T. and Conway, P.M. (1999) 'The effect of tillage regime, row spacing, and seeding rate on feeding damage by flea beetles, Phyllotreta spp.(Coleoptera: Chrysomelidae), in canola in central Alberta, Canada'. Crop Protection, 18(3), pp.217-224.

Duan, Y.-h., SHI, X.-j., LI, S.-l., SUN, X.-f. and HE, X.-h. (2014) 'Nitrogen use efficiency as affected by phosphorus and potassium in long-term rice and wheat experiments', Journal of Integrative Agriculture, 13(3), pp. 588-596.

Engström, L., Stenberg, M., Aronsson, H. and Lindén, B. (2011) 'Reducing nitrate leaching after winter oilseed rape and peas in mild and cold winters', Agronomy for Sustainable Development, 31(2), pp. 337-347.

EPA. (2020). Greenhouse gas emissions from agriculture. Available Online: http://epa.ie/ghg/agriculture/.

Farm to Fork Strategy. Available Online: https://ec.europa.eu/food/horizontal-topics/farm-fork-strategy_en.

Ferreira, M., Satagopan, J., Yandell, B., Williams, P. and Osborn, T. (1995) 'Mapping loci controlling vernalization requirement and flowering time in *Brassica napus*', Theoretical and Applied Genetics, 90(5), pp. 727-732.

Fletcher, S. M., Dench, J.A.L. Vaughan, R.L. 1976. oilseed Rape:Agricultural Enterprise studies in England and Wales. Economic Report No.41. Reading: Reading University.

Forde, B.G. and Clarkson, D.T. (1999) 'Nitrate and ammonium nutrition of plants: physiological and molecular perspectives'. In *Advances in botanical research* (Vol. 30, pp. 1-90). Academic Press.

Forrestal, P., Meisinger, J. and Kratochvil, R. (2014) 'Winter wheat starter nitrogen management: A preplant soil nitrate test and site-specific nitrogen loss potential', Soil Science Society of America Journal, 78(3), pp. 1021-1034.

Forristal, P. and Grant, J. (2011) 'The impact of break-crop and cereal rotations on crop performance and profit margins', Aspects of Applied Biology, (113), pp. 29-36.

Franzaring, J., Högy, P. and Fangmeier, A. (2008) 'Effects of free-air CO2 enrichment on the growth of summer oilseed rape (*Brassica napus* cv. *Campino*) '. Agriculture, ecosystems & environment, 128(1-2), pp.127-134.

Fray, M., Evans, E., Lydiate, D. and Arthur, A. (1996) 'Physiological assessment of apetalous flowers and erectophile pods in oilseed rape (Brassica napus)', The Journal of Agricultural Science, 127(2), pp. 193-200.

Frenck, G., van der Linden, L., Mikkelsen, T. N., Brix, H. and Jørgensen, R. B. (2011) 'Increased [CO_2] does not compensate for negative effects on yield caused by higher temperature and [O_3] in Brassica napus L', European Journal of Agronomy, 35(3), pp. 127-134.

Früchtenicht, K. (1965) 'Die Ermittlung des zusätzlichen Stickstoffbedarfs in Getreidebeständen zur Zeit des Schossens'. Doctoral dissertation, Verlag nicht ermittelbar.

Gabrielle, B., Denoroy, P., Gosse, G., Justes, E. and Andersen, M. N. (1998a) 'Development and evaluation of a CERES-type model for winter oilseed rape', Field Crops Research, 57(1), pp. 95-111.

Gabrielle, B., Denoroy, P., Gosse, G., Justes, E. & Andersen, M. N. (1998b) 'A model of leaf area development and senescence for winter oilseed rape'. Field Crops Research, 57, 209-222.

Gammelvind, L. H., Schjoerring, J. K., Mogensen, V. O., Jensen, C. R. and Bock, J. G. H. (1996) 'Photosynthesis in leaves and siliques of winter oilseed rape (*Brassica napus* L.)', Plant and Soil, 186(2), pp. 227-236.

Gavaliene, V., Novickiene, L., Miliuviene, L., & Brazauskiene, I. (1998) 'The effect of growth regulators on wheat and rape wintering'. Babtai, 17, 195206

George, B. (1984) 'Design and interpretation of nitrogen response experiments'. Nitrogen requirement of cereals: proceedings of a conference organised by the Agricultural Development and Advisory Service, September 1982: London: HMSO, 1984.

Gilmour, J. T. (1998) 'Carbon and nitrogen mineralization during co-utilization of biosolids and composts', beneficial co-utilization of agricultural, municipal, and industrial by-products: Springer, pp. 89-112.

Gilmour, J. T., Clark, M. D. and Daniel, S. M. (1996) 'Predicting long-term decomposition of biosolids with a seven-day test', Journal of Environmental Quality, 25(4), pp. 766-770.

Gilmour, J. T. and Skinner, V. (1999) 'Predicting plant available nitrogen in land-applied biosolids', Journal of Environmental Quality, 28(4), pp. 1122-1126.

Girondé, A., Etienne, P., Trouverie, J., Bouchereau, A., Le Cahérec, F., Leport, L., Orsel, M., Niogret, M.-F., Nesi, N. and Carole, D. (2015) 'The contrasting N management of two oilseed rape genotypes reveals the mechanisms of proteolysis associated with leaf N remobilization and the respective contributions of leaves and stems to N storage and remobilization during seed filling', BMC plant biology, 15(1), pp. 59.

Good, A. G., Shrawat, A. K. and Muench, D. G. (2004) 'Can less yield more? Is reducing nutrient input into the environment compatible with maintaining crop production?' Trends in plant science, 9 (12), pp. 597-605.

Goulding, K. W. (1990) 'Nitrogen deposition to land from the atmosphere', Soil Use and Management, 6(2), pp. 61-63.

Graham, C.W. and Alford, D.V.(1981) 'The distribution and importance of cabbage stem flea beetle (*Psylliodes chrysocephala* (L.)) on winter oilseed rape in England'. *Plant Pathology*, *30*(3), pp.141-145.

Grant, C.A. and Bailey, L.D., 1993. Fertility management in canola production. *Canadian Journal of Plant Science*, *73*(3), pp.651-670.

Grant, C.A., Wu, R., Selles, F., Harker, K.N., Clayton, G.W., Bittman, S., Zebarth, B.J. and Lupwayi, N.Z., 2012. Crop yield and nitrogen concentration with controlled release urea and split applications of nitrogen as compared to non-coated urea applied at seeding. *Field Crops Research*, *127*, pp.170-180.

Grzebisz, W., Łukowiak, R. and Sassenrath, G. F. (2018) 'Virtual nitrogen as a tool for assessment of nitrogen management at the field scale: A crop rotation approach', Field Crops Research, 218, pp. 182-194.

Guyot, G. (1990) 'Optical properties of vegetation canopies', Applications of remote sensing in agriculture, Butterworths. ⟨hal-02852761⟩. pp. 19-43.

Guyot, G., Baret, F. and Jacquemoud, S. (1992) 'Imaging spectroscopy for vegetation studies', Imaging spectroscopy: Fundamentals and prospective application, 2, pp. 145-165.

Habekotte, B. (1997) 'Evaluation of seed yield determining factors of winter oilseed rape (*Brassica napus* L.) by means of crop growth modelling', Field Crops Research, 54(2-3), pp. 137-151.

Hadas, A., Kautsky, L., Goek, M. and Kara, E. E. (2004) 'Rates of decomposition of plant residues and available nitrogen in soil, related to residue composition through simulation of carbon and nitrogen turnover', Soil Biology and Biochemistry, 36(2), pp. 255-266.

Håkansson, I. and von Polgár, J. (1984) 'Experiments on the effects of seedbed characteristics on seedling emergence in a dry weather situation', Soil and Tillage Research, 4(2), pp. 115-135.

Hamelinck, C., De Lovinfosse, I., Koper, M., Beestermoeller, C., Nabe, C., Kimmel, M., Van den Bos, A., Yildiz, I., Harteveld, M. and Ragwitz, M. (2013) 'Renewable energy progress and biofuels sustainability'. (No. ENER/C1/463-2011-Lot2).

Hartman, M. (2012) 'Canola rotation performance', Proc. FarmTech, pp. 24-26.

Harty, M. A., Forrestal, P. J., Watson, C., McGeough, K., Carolan, R., Elliot, C., Krol, D., Laughlin, R. J., Richards, K. G. and Lanigan, G. (2016) 'Reducing nitrous oxide emissions by changing N fertiliser use from calcium ammonium nitrate (CAN) to urea based formulations', Science of the Total Environment, 563, pp. 576-586.

Hattori, H. and Mukai, S. (1986) 'Decomposition of sewage sludges in soil as affected by their organic matter composition', Soil Science and Plant Nutrition, 32(3), pp. 421-432.

Haynes, R. (1982) 'Effects of liming on phosphate availability in acid soils', Plant and Soil, 68(3), pp. 289-308.

Heap, I. The International Herbicide-Resistant Weed Database. Online. Thursday, August 4, 2022. Available www.weedscience.org . WeedScience.org

Heap, I. and Duke, S.O. (2018) 'Overview of glyphosate-resistant weeds worldwide'. Pest management science, 74(5), pp.1040-1049.

Hebinger, H. and Pinochet, X. L. (2013) 'Plante: classification botanique, elaboration du rendement, selection', Le colza. Paris France, pp. 59-149.

Hegewald, H., Wensch-Dorendorf, M., Sieling, K. and Christen, O. (2018) 'Impacts of break crops and crop rotations on oilseed rape productivity: A review', European Journal of Agronomy, 101, pp. 63-77.

Herlihy, M. (1976) 'the Effects of Soil Texture, Moisture and Organic Matter on the Mineralisation and Availability of Nitrogen'. (Doctoral dissertation, University College Dublin).

Henke, J., Sieling, K., Sauermann, W. and Kage, H. (2009) 'Analysing soil and canopy factors affecting optimum nitrogen fertilization rates of oilseed rape (*Brassica napus*)', The Journal of Agricultural Science, 147(1), pp. 1-8.

Ho CH, Lin SH, Hu HC, Tsay YF. (2009) 'CHL1 functions as a nitrate sensor in plants'. Cell 138, 1184–1194.

Holmes, M. R. and Ainsley, A. M. (1979) 'Nitrogen top-dressing requirements of winter oilseed rape', Journal of the Science of Food and Agriculture, 30(2), pp. 119-128.

Honeycutt, C., Potaro, L., Avila, K. and Halteman, W. (1993) 'Residue quality, loading rate and soil temperature relations with hairy vetch (*Vicia villosa Roth*) residue carbon, nitrogen and phosphorus mineralization', Biological Agriculture & Horticulture, 9(3), pp. 181-199.

Horst, W., Behrens, T., Heuberger, H., Kamh, M., Reidenbach, G. and Wiesler, F. (2003) 'Genotypic differences in nitrogen use-efficiency in crop plants', Innovative Soil–Plant Systems for Sustainable Agricultural Production, pp. 75-92.

Humphreys, J. (2007) 'Cutting back on fertilizer for grassland in 2007', Proceedings of the Fertilizer Association of Ireland, 43, pp. 2-35.

Inglis, I., Thearle, R. & Isaacson, A. (1989) 'Woodpigeon (Columba palumbus) damage to oilseed rape'. *Crop Protection,* 8**,** 299-309.

Inselsbacher, E. and Näsholm, T. (2012) 'A novel method to measure the effect of temperature on diffusion of plant-available nitrogen in soil', Plant and Soil, 354(1-2), pp. 251-257.

James, D. W. (1968) 'Predicting the Nitrogen Fertilizer Requirements of Sugar Beets Grown in Central Washington: 1967 Research Results'. Washington Agricultural Experiment Station, College of Agriculture.

Jenkins, P. and Leitch, D. M. (1986) 'Effects of sowing date on the growth and yield of winter oilseed rape (*Brassica napus*)', The Journal of Agricultural Science, 107(2), pp. 405-420.

Juma, N., Paul, E. and Mary, B. (1984) 'Kinetic Analysis of Net Nitrogen Mineralization in Soil 1', Soil Science Society of America Journal, 48(4), pp. 753-757.

Jungk, A. and Claassen, N. (1997) 'Ion diffusion in the soil-root system', Advances in agronomy, USA.

Justes, E., Denoroy, P., Gabrielle, B. and Gosse, G. (2000) 'Effect of crop nitrogen status and temperature on the radiation use efficiency of winter oilseed rape', European Journal of Agronomy, 13(2-3), pp. 165-177.

Kantolic, A. G. and Slafer, G. A. (2001) 'Photoperiod sensitivity after flowering and seed number determination in indeterminate soybean cultivars', Field Crops Research, 72(2), pp. 109-118.

Keeney, D. R. (1983) 'Nitrogen—availability indices', Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties, 9, pp. 711-733.

Kelly, J. and Mays, P. (1999) 'Nutrient supply changes within a growing season in two deciduous forest soils', Soil Science Society of America Journal, 63(1), pp. 226-232.

Kersebaum, K. C. (2007) 'Modelling nitrogen dynamics in soil–crop systems with HERMES', *Modelling water and nutrient dynamics in soil–crop systems*: Springer, pp. 147-160.

Kiba T, Krapp A. (2016) 'Plant nitrogen acquisition under low availability: regulation of uptake and root architecture'. Plant & Cell Physiology 57, 707–714.

Kindred, D. R., Knight, S. M., Berry, P. M., Sylvester-Bradley, R., Hatley, D., Morris, N. Z., Hoad, S. and White, C. A. (2012) 'Establishing best practice for estimation of Soil N Supply'. HGCA. London: UK.

Kindred, D. and Sylvester-Bradley, R. (2014) 'Using Precision Farming technologies to improve nitrogen management and empower on-farm learning', Aspects of Applied Biology, 127, pp. 173-180.

Kirkegaard, J., Christen, O., Krupinsky, J. and Layzell, D. (2008) 'Break crop benefits in temperate wheat production', Field Crops Research, 107(3), pp. 185-195.

Kirkegaard, J., Sprague, S., Lilley, J., McCormick, J., Virgona, J. and Morrison, M. (2012) 'Physiological response of spring canola (*Brassica napus*) to defoliation in diverse environments', Field Crops Research, 125, pp. 61-68.

Kirkegaard, J. A., Lilley, J. M. and Morrison, M. J. (2016) 'Drivers of trends in Australian canola productivity and future prospects', Crop and Pasture Science, 67(4), pp. i-ix.

Kirkegaard, J. A., Lilley, J. M., Berry, P. M. and Rondanini, D. P. (2021) 'Canola', Crop Physiology Case Histories for Major Crops: Elsevier, pp. 518-549.

Kitchen, N. and Goulding, K. (2001) 'On-farm technologies and practices to improve nitrogen use efficiency', in Follet, R.F.andHatfield, J.L. (eds.) Nitrogen in the environment: Sources, problems and management. Elsevier, Amsterdam: The Netherlands. pp 334-370.

Kotur Z, Siddiqi YM, Glass AD. (2013) 'Characterization of nitrite uptake in Arabidopsis thaliana: evidence for a nitrite-specific transporter'. The New Phytologist 200, 201–210.

Lemaire, G. and Gastal, F.(1997) 'N uptake and distribution in plant canopies'. In Diagnosis of the nitrogen status in crops (pp. 3-43). Springer, Berlin, Heidelberg.

Lammel, J., Wollring, J. and Reusch, S. (2001) 'Tractor based remote sensing for variable nitrogen fertilizer application', Plant Nutrition: Springer, pp. 694-695.

Lancashire, P. D., Bleiholder, H., Boom, T. V. D., Langelüddeke, P., Stauss, R., Weber, E. and Witzenberger, A. (1991) 'A uniform decimal code for growth stages of crops and weeds', Annals of Applied Biology, 119(3), pp. 561-601.

LANE, A. (1983) 'Benefits and hazards of new crops: oilseed rape in the UK'. Agriculture, ecosystems & environment, 10**,** 299-309.

Lanigan, G., Donnellan, T., Hanrahan, K., Carsten, P., Shalloo, L., Krol, D., Forrestal, P. J., Farrelly, N., O'Brien, D. and Ryan, M. (2018) 'An analysis of abatement potential of Greenhouse Gas emissions in Irish agriculture 2021-2030': Teagasc Agriculture and Food Development Authority.

Lardon, A. and Triboi-Blondel, A. (1995) 'Cold and freeze stress at flowering Effects on seed yields in winter rapeseed', Field Crops Research, 44(2-3), pp. 95-101.

Leach, J., Stevenson, H., Rainbow, A. and Mullen, L. (1999) 'Effects of high plant populations on the growth and yield of winter oilseed rape (*Brassica napus*)', The Journal of Agricultural Science, 132(2), pp. 173-180.

Lemaire, G., van Oosterom, E., Jeuffroy, M.-H., Gastal, F. and Massignam, A. (2008) 'Crop species present different qualitative types of response to N deficiency during their vegetative growth', Field Crops Research, 105(3), pp. 253-265.

Li, H., Cong, R., Ren, T., Li, X., Ma, C., Zheng, L., Zhang, Z. and Lu, J. (2015) 'Yield response to N fertilizer and optimum N rate of winter oilseed rape under different soil indigenous N supplies', Field Crops Research, 181, pp. 52-59.

Li, C., Farahbakhshazad, N., Jaynes, D.B., Dinnes, D.L., Salas, W. and McLaughlin, D. (2006) 'Modelling nitrate leaching with a biogeochemical model modified based on observations in a row-crop field in Iowa'. Ecological modelling, 196(1-2), pp.116-130.

Li, H., Li, R., Zhu, H. and Wu, L. (2010a) 'Influence of electrostatic field from soil particle surfaces on ion adsorption–diffusion', Soil Science Society of America Journal, 74(4), pp. 1129-1138.

Li, J., Zhang, M., Kong, Q., Yao, B., Yan, M. and LIN, Q. (2010b) 'Soil testing and formula fertilization index for early rice in Fujian province', Plant Nutrition and Fertilizer Science, 4, pp. 025.

Li, C.S.(2000) 'Modelling trace gas emissions from agricultural ecosystems'. In Methane emissions from major rice ecosystems in Asia (pp. 259-276). Springer, Dordrecht.

Lilley, J. M., Flohr, B. M., Whish, J. P., Farre, I. and Kirkegaard, J. A. (2019) 'Defining optimal sowing and flowering periods for canola in Australia', Field Crops Research, 235, pp. 118-128.

Liu, S., Li, L., Gao, W., Zhang, Y., Liu, Y., Wang, S. and Lu, J. (2018) 'Diagnosis of nitrogen status in winter oilseed rape (*Brassica napus* L.) using in-situ hyperspectral data and unmanned aerial vehicle (UAV) multispectral images', Computers and Electronics in Agriculture, 151, pp. 185-195.

Luce, M.S., Grant, C.A., Ziadi, N., Zebarth, B.J., O'Donovan, J.T., Blackshaw, R.E., Harker, K.N., Johnson, E.N., Gan, Y., Lafond, G.P. and May, W.E. (2016). 'Preceding crops and nitrogen fertilization influence soil nitrogen cycling in no-till canola and wheat cropping systems'. Field Crops Research, 191, pp.20-32.

Lunn, G., Spink, J., Stokes, D., Wade, A., Clare, R. and Scott, R. (2001) 'Canopy management in winter oilseed rape'. HGCA Project Report No. OS49. London: UK, pp.86.

Lunn, G., Spink, J., Wade, A. and Clare, R. (2003) 'Spring remedial treatments to improve canopy structure and yield in oilseed rape', HGCA Project Report No. OS64, pp. 97.

Lääniste, P., Jõudu, J. and Eremeev, V. (2004) 'Oil content of spring oilseed rape seeds according to fertilisation. *Agronomy research*, *2*(1), pp.83-86.

Lääniste, P., Jõudu, J., Eremeev, v. and mäeorg, E. (2007) 'Sowing date influence on winter oilseed rape overwintering in Estonia', Acta Agriculturae Scandinavica Section B-Soil and Plant Science, 57(4), pp. 342-348.

Läpple, D., Carter, C. A. and Buckley, C. (2022) 'EU milk quota abolition, dairy expansion, and greenhouse gas emissions', Agricultural Economics, 53(1), pp. 125-142.

Łukowiak, R. and Grzebisz, W. (2020) 'Effect of site specific nitrogen management on seed nitrogen—A driving factor of winter oilseed rape (*Brassica napus* L.) yield', Agronomy, 10(9), pp. 1364.

Ma, B.L., Subedi, K.D. and Costa, C. (2005). 'Comparison of crop-based indicators with soil nitrate test for corn nitrogen requirement'. Agronomy Journal, 97(2), pp.462-471.

Ma, B.L., Subedi, K.D. and Dwyer, L.M. (2006). 'Timing and method of 15nitrogen-labeled fertilizer application on grain protein and nitrogen use efficiency of spring wheat'. Journal of plant nutrition, 29(3), pp.469-483.

Ma, B.L., Subedi, K.D. and Zhang, T.Q. (2007) 'Pre-Sidedress Nitrate Test and Other Crop-Based Indicators for Fresh Market and Processing Sweet Corn'. Agronomy Journal, 99(1), pp.174-183.

Ma, B.L., Biswas, D.K., Herath, A.W., Whalen, J.K., Ruan, S.Q., Caldwell, C., Earl, H., Vanasse, A., Scott, P. and Smith, D.L (2015) 'Growth, yield, and yield components of canola as affected by nitrogen, sulfur, and boron application'. Journal of Plant Nutrition and Soil Science, 178(4), pp.658-670.

Ma, B.L. and Herath, A.W. (2016) 'Timing and rates of nitrogen fertiliser application on seed yield, quality and nitrogen-use efficiency of canola'. Crop and pasture Science, 67(2), pp.167-180.

Maier, U., Kudlinski, J. and Müller-Westermeier, G. (2003) 'Klimatologische Auswertung von Zeitreihen des Monatsmittels der Lufttemperatur und der monatlichen Niederschlagshöhe im 20'. Jahrhundert. Selbstverlag des Deutschen Wetterdienstes Offenbach am Main.

Makowski, D., Maltas, A., Morison, M. and Reau, R. (2005) 'Calculating N fertilizer doses for oil-seed rape using plant and soil data', Agronomy for Sustainable Development, 25(1), pp. 159-161.

Malagoli, P., Lainé, P., Le Deunff, E., Rossato, L., Ney, B. and Ourry, A. (2004) 'Modeling nitrogen uptake in oilseed rape cv Capitol during a growth cycle using influx kinetics of root nitrate transport systems and field experimental data', Plant physiology, 134(1), pp. 388-400.

Masclaux-Daubresse, C., Reisdorf-Cren, M. and Orsel, M. (2008) 'Leaf nitrogen remobilisation for plant development and grain filling', Plant Biology, 10, pp. 23-36.

Mayes, J. and Wheeler, D. (2013) 'Regional weather and climates of the British Isles-Part 1: Introduction', Weather, 68(1), pp. 3-8.

McWilliam, S., Stafford, J., Scott, R., Norton, G., Stokes, D. and Sylvester-Bradley, R. (1995) 'The relationship between canopy structure and yield in oilseed rape'. Proceedings of the 9th International Rapeseed Congress Volume, 485-490.

McWilliam, S., Stokes, D. and Scott, R. (1998) 'Establishment of oilseed rape: the influence of physical characteristics of seedbeds and weather on germination, emergence and seedling survival', HGCA Project Report NO. OS31.

McWilliam, S., Stokes, D., Scott, R., Norton, G., Sylvester-Bradley, R. and Davies, D. (1995) 'The relationship between establishment and yield of autumn-sown oilseed rape', HGCA Oilseeds Project Report (United Kingdom). Project No. OS08/01/91.

Meckel, L., Egli, D., Phillips, R., Radcliffe, D. and Leggett, J. (1984) 'Effect of Moisture Stress on Seed Growth in Soybeans 1', Agronomy Journal, 76(4), pp. 647-650.

Meisinger, J., Bandel, V., Angle, J., O'keefe, B. and Reynolds, C. (1992) 'Presidedress soil nitrate test evaluation in Maryland', Soil Science Society of America Journal, 56(5), pp. 1527-1532.

Mendham, N., Shipway, P. and Scott, R. (1981a) 'The effects of delayed sowing and weather on growth, development, and yield of winter oil-seed rape (*Brassica napus*)', The Journal of Agricultural Science, 96(2), pp. 389-416.

Mendham, N. J., Shipway, P. A. and Scott, R. K. (1981b) 'The effects of seed size, autumn nitrogen and plant population density on the response to delayed sowing in winter oil-seed rape (*Brassica napus*)', The Journal of Agricultural Science, 96(2), pp. 417-428.

Mendham, N. J. and Salisbury, P. (1995) 'Physiology: Crop Development, Growth and Yield', Brassica oilseeds Production and Utilisation. Kimber D., McGregor, D.I. ed. Wallingford (UK): CAB International, pp. 11-64.

Merrien, A. and Pouzet, A. (1988) 'The principal yield-limiting factors in winter rape under French conditions', Physiologie et élaboration du rendement du colza d'hiver., pp. 16-19.

Met Eireann. Available Online: https://www.met.ie/climate/available-data/historical-data.

Meteofrance.fr/climat-passe-et-futur/climat-en-france/le-climat-en-metropole.

Met Office. Available Online: https://www.metoffice.gov.uk/research/climate/seasonal-to-decadal/operational-systems.

Micks, P., Aber, J. D., Boone, R. D. and Davidson, E. A. (2004) 'Short-term soil respiration and nitrogen immobilization response to nitrogen applications in control and nitrogen-enriched temperate forests', Forest Ecology and Management, 196(1), pp. 57-70.

Miller AJ, Cramer MD. (2004) 'Root nitrogen acquisition and assimilation'. Plant and Soil 274, 1–36.

Mogensen, V., Jensen, C., Mortensen, G., Andersen, M., Schjoerring, J., Thage, J. and Koribidis, J. (1997) 'Pod photosynthesis and drought adaptation of field grown rape (*Brassica napus* L.)', European Journal of Agronomy, 6(3-4), pp. 295-307.

Moll, R., Kamprath, E. and Jackson, W. (1982) 'Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization 1', Agronomy Journal, 74(3), pp. 562-564.

Monteith, J. (1965) 'Light distribution and photosynthesis in field crops', Annals of botany, 29(1), pp. 17-37.

Monteith, J. L. (1977) 'Climate and the efficiency of crop production in Britain', Philosophical Transactions of the Royal Society of London. B, Biological Sciences, 281(980), pp. 277-294.

Moritsuka, N., Yanai, J., Mori, K. and Kosaki, T. (2004) 'Biotic and abiotic processes of nitrogen immobilization in the soil-residue interface', Soil Biology and Biochemistry, 36(7), pp. 1141-1148.

Morris, D.A. (1996) 'Hormonal regulation of source-sink relationships: an overview of potential control mechanisms. (pp. 441465)'. Photoassimilate Distribution in Plants and Crops. Source-Sink Relationships. Hong Kong,

Morrison, M., Harker, K., Blackshaw, R., Holzapfel, C. and O'Donovan, J. (2016) 'Canola yield improvement on the Canadian Prairies from 2000 to 2013', Crop and Pasture Science, 67(4), pp. 245-252.

Müller-Westermeier, G. (1995) Numerisches Verfahren zu Erstellung klimatologischer Karten. Deutscher Wetterdienst. Available Online: https://www.dwd.de/DE/leistungen/pbfb_verlag_berichte/pdf_einzelbaende/193_pdf.pdf?__blob=publicationFile&v=3.

Nagaharu, U. and Nagaharu, N. (1935) 'Genome analysis in Brassica with special reference to the experimental formation of *B. napus* and peculiar mode of fertilization'.

Nmmik, H. (1966) 'The residual effects of nitrogen fertilizers in relation to the quantities of mineral nitrogen recovered in the soil profile', Acta Agriculturae Scandinavica, 16(3-4), pp. 163-178.

Nyikako, J., Schierholt, A., Kessel, B. and Becker, H. C. (2014) 'Genetic variation in nitrogen uptake and utilization efficiency in a segregating DH population of winter oilseed rape', Euphytica, 199(1-2), pp. 3-11.

O'Brien JA, Vega A, Bouguyon E, Krouk G, Gojon A, Coruzzi G, Gutiérrez RA. (2016) 'Nitrate transport, sensing, and responses in plants'. Molecular Plant 9, 837–856.

Olfs, H. and Werner, W. (1993) 'Methodische Ansätze zur Erfassung des N-Nachlieferungsvermögens des Bodens', Berichte über Landwirtschaft, 207, pp. 141-157.

Olfs, H. W., Blankenau, K., Brentrup, F., Jasper, J., Link, A. and Lammel, J. (2005) 'Soil-and plant-based nitrogen-fertilizer recommendations in arable farming', Journal of Plant Nutrition and Soil Science, 168(4), pp. 414-431.

Petersen, C.T., Jørgensen, U., Svendsen, H., Hansen, S., Jensen, H.E. and Nielsen, N.E. (1995) 'Parameter assessment for simulation of biomass production and nitrogen uptake in winter rape'. European Journal of Agronomy, 4(1), pp.77-89.

Pouzet, A. (1995) 'Agronomy', Brassica oilseeds Production and Utilisation. Kimber D., McGregor, D.I. ed. Wallingford (UK): CAB International, pp. 65-92.

Powlson, D., Stockdale, E., Jarvis, S. and Shepherd, M. (1994) 'A review of nitrogen mineralization and immobilization in UK agricultural soils', A review prepared for MAFF London, UK.

Puri, G. and Ashman, M. (1999) 'Microbial immobilization of ^{15}N-labelled ammonium and nitrate in a temperate woodland soil', Soil biology & biochemistry, 31(6), pp. 929-931.

Raman, H., Raman, R., Prangnell, R., Eckermann, P., Edwards, D., Batley, J., Coombes, N., Taylor, B., Wratten, N. and Luckett, D. (2011) 'Genetic dissection of natural variation for flowering time in rapeseed'. Proceedings of the 13th International Rapeseed Congress, Prague: Czech, 139.

Rathke, G.-W., Behrens, T. and Diepenbrock, W. (2006) 'Integrated nitrogen management strategies to improve seed yield, oil content and nitrogen efficiency of winter oilseed rape (*Brassica napus* L.): a review', Agriculture, ecosystems & environment, 117(2-3), pp. 80-108.

Ray, D. K., West, P. C., Clark, M., Gerber, J. S., Prishchepov, A. V. and Chatterjee, S. (2019) 'Climate change has likely already affected global food production', PloS one, 14(5), pp. e0217148.

Räbiger, T., Andres, M., Hegewald, H., Kesenheimer, K., Köbke, S., Quinones, T. S., Böttcher, U. and Kage, H. (2020) 'Indirect nitrous oxide emissions from oilseed rape cropping systems by NH_3 volatilization and nitrate leaching as affected by nitrogen source, N rate and site conditions', European Journal of Agronomy, 116, pp. 126039.

Reau R., Wagner D., Palleau J.P. (1994) 'End of winter diagnosis: Winter rapeseed and nitrogen fertilization', in: Borin M., Sattin M. (Eds.), Proceedings of the third congress of the European Society for Agronomy, Podova: European Society for Agronomy, pp. 220–221.

Recous, S., Machet, J. and Mary, B. (1992) 'The partitioning of fertilizer-N between soil and crop: Comparison of ammonium and nitrate applications', Plant and Soil, 144(1), pp. 101-111.

Recous, S., Mary, B. and Faurie, G. (1990) 'Microbial immobilization of ammonium and nitrate in cultivated soils', Soil Biology and Biochemistry, 22(7), pp. 913-922.

Ren, T., Li, H., Lu, J., Bu, R., Li, X., Cong, R. and Lu, M. (2015) 'Crop rotation-dependent yield responses to fertilization in winter oilseed rape (*Brassica napus* L.)', The Crop Journal, 3(5), pp. 396-404.

Rice, C. W., Haviin, J. L. and Schepers, J. S. (1995) 'Rational nitrogen fertilization in intensive cropping systems', Nitrogen Economy in Tropical Soils: Springer, pp. 89-97.

Richter, J., Nuske, A., Habenicht, W. and Bauer, J. (1982) 'Optimized N-mineralization parameters of loess soils from incubation experiments', *Plant and Soil*, 68(3), pp. 379-388

Robertson, G.P. and Vitousek, P.M. (2009) 'Nitrogen in agriculture: balancing the cost of an essential resource'. Annual review of environment and resources, 34, pp.97-125.

Robertson, M., Asseng, S., Kirkegaard, J., Wratten, N., Holland, J., Watkinson, A., Potter, T., Burton, W., Walton, G. and Moot, D. (2002) 'Environmental and genotypic control of time to flowering in canola and Indian mustard', Australian Journal of Agricultural Research, 53(7), pp. 793-809.

Rodgers, G., Penny, A. and Hewitt, M. (1986) 'A comparison of the effects of prilled urea, used alone or with a nitrification or urease inhibitor, with those of ‘Nitro-Chalk’', The Journal of Agricultural Science, 106(3), pp. 515-526.

Rossato, L., Lainé, P. and Ourry, A. (2001) 'Nitrogen storage and remobilization in Brassica napus L. during the growth cycle: nitrogen fluxes within the plant and changes in soluble protein patterns', Journal of Experimental Botany, 52(361), pp. 1655-1663.

Rouse Jr, J. W., Haas, R. H., Schell, J. and Deering, D. (1973) 'Monitoring the vernal advancement and retrogradation (green wave effect) of natural vegetation'.

Ruser, R., Fuß, R., Andres, M., Hegewald, H., Kesenheimer, K., Köbke, S., Räbiger, T., Quinones, T. S., Augustin, J. and Christen, O. (2017) 'Nitrous oxide emissions from winter oilseed rape cultivation', Agriculture, ecosystems & environment, 249, pp. 57-69.

Scharpf, H. (1977) Der Mineralstickstoffgehalt des Bodens als Maßstab für den Stickstoffdüngerbedarf. Ph.D. thesis, University of Hanover, Germany.

Scharpf, H. and Wehrmann, J. (1976) 'Bedeutung des Mineralstickstoffvorrates des Bodens zu Vegetationsbeginn fur die Bemessung der N Dungung zu Winterweizen', Landwirtschaftliche Forschung. Sonderheft.

Schnabel, R. R., Franzluebbers, A. J., Stout, W. L., Sanderson, M. A. and Stuedemann, J. A. (2001) 'The effects of pasture management practices. The potential of U.S. grazing land to sequester carbon and mitigate the greenhouse effect' FL: Lewis Edition. Boca Raton, p. 291-322.

Schröder, J., Neeteson, J., Oenema, O. and Struik, P. (2000) 'Does the crop or the soil indicate how to save nitrogen in maize production?: Reviewing the state of the art', Field Crops Research, 66(2), pp. 151-164.

Schulte auf‘m Erley, G., Behrens, T., Ulas, A., Wiesler, F. and Horst, W. J. (2011) 'Agronomic traits contributing to nitrogen efficiency of winter oilseed rape cultivars', Field Crops Research, 124(1), pp. 114-123.

Scott, R.K., Ogunremi, E.A., Ivins, J.D. and Mendham, N.J. (1973) 'The effect of fertilizers and harvest date on growth and yield of oilseed rape sown in autumn and spring'. The Journal of Agricultural Science, 81(2), pp.287-293.

Shen QR, Ran W, Cao ZH. (2003) 'Mechanisms of nitrite accumulation occurring in soil nitrification'. Chemosphere 50, 747–753.

Shepherd, M., Stockdale, E., Powlson, D. and Jarvis, S. (1996) 'The influence of organic nitrogen mineralization on the management of agricultural systems in the UK', Soil Use and Management, 12(2), pp. 76-85.

Shepherd, M. and Sylvester-Bradley, R. (1996) 'Effect of nitrogen fertilizer applied to winter oilseed rape (*Brassica napus*) on soil mineral nitrogen after harvest and on the response of a succeeding crop of winter wheat to nitrogen fertilizer', The Journal of Agricultural Science, 126(1), pp. 63-74.

Shukla, P., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H., Roberts, D., Zhai, P., Slade, R., Connors, S. and Van Diemen, R. (2019)' IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems'.

Sieling, K., Günther-Borstel, O., Teebken, T. and Hanus, H. (1999) 'Soil mineral N and N net mineralization during autumn and winter under an oilseed rape–winter wheat–winter barley rotation in different crop management systems', The Journal of Agricultural Science, 132(2), pp. 127-137.

Sieling, K. (2000) 'Untersuchungen zu den Auswirkungen unterschiedlicher Produktionssysteme auf einige Parameter des N-Haushaltes von Boden und Pflanze'. Lehrstuhl Pflanzenbau.

Sieling, K. and Kage, H. (2006) ' N balance as an indicator of N leaching in an oilseed rape–winter wheat–winter barley rotation', Agriculture, ecosystems & environment, 115(1-4), pp. 261-269.

Sieling, K., Stahl, C., Winkelmann, C. and Christen, O. (2005) 'Growth and yield of winter wheat in the first 3 years of a monoculture under varying N fertilization in NW Germany', European Journal of Agronomy, 22(1), pp. 71-84.

Sieling, K., Böttcher, U. and Kage, H. (2017a) 'Sowing date and N application effects on tap root and above-ground dry matter of winter oilseed rape in autumn', European Journal of Agronomy, 83, pp. 40-46.

Sieling, K., Böttcher, U. and Kage, H. (2017b) 'Effect of sowing method and N application on seed yield and N use efficiency of winter oilseed rape', *Agronomy*, 7(1), pp. 21.

Smith, P. (2008) 'Land use change and soil organic carbon dynamics', Nutrient Cycling in Agroecosystems, 81(2), pp. 169-178.

Smith, V. H. and Schindler, D. W. (2009) 'Eutrophication science: where do we go from here? ' Trends in ecology & evolution, 24(4), pp. 201-207.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U. and Towprayoon, S. (2007) 'Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture', Agriculture, ecosystems & environment, 118(1), pp. 6-28.

Sommer, S. G., Schjoerring, J. K. and Denmead, O. (2004) 'Ammonia emission from mineral fertilizers and fertilized crops', Advances in agronomy, 82(557622), pp. 82008-4.

Soper, R. and Huang, P. (1963) 'The effect of nitrate nitrogen in the soil profile on the response of barley to fertilizer nitrogen', Canadian Journal of Soil Science, 43(2), pp. 350-358.

Söchting, H.P. and Verreet, J.A. (2004) 'Effects of different cultivation systems (soil management, nitrogen fertilization) on the epidemics of fungal diseases in oilseed rape (*Brassica napus* L. var. *napus*)'. Journal of Plant Diseases and Protection, 111(1), pp.1-29.

Spink, J. (1992) 'Winter oilseed rape: effect of partial defoliation', HGCA Oilseeds Project Report No. OS4. UK.

Spink, J., Lunn, G., Clare, R. and Foulkes, M. (2003) 'Sowing date and seed rate in wheat and oilseed rape'. Proceedings of the eighth HGCA R&D Conference on cereals and oilseeds, 3.1-7.13.

Spink, J., Street, P., Sylvester-Bradley, R. and Berry, P. (2009) 'The potential to increase productivity of wheat and oilseed rape in the UK: Professor John Beddington'. Report to the Government Chief Scientific Advisor.

Sprague, S. J., Balesdent, M.-H., Brun, H., Hayden, H. L., Marcroft, S. J., Pinochet, X., Rouxel, T. and Howlett, B. J. (2006) 'Major gene resistance in *Brassica napus* (oilseed rape) is overcome by changes in virulence of populations of *Leptosphaeria maculans* in France and Australia', Sustainable strategies for managing *Brassica napus* (oilseed rape) resistance to *Leptosphaeria maculans* (phoma stem canker): Springer, pp. 33-40.

Stafford, J. A. (1996) 'The effects of prochloraz on the growth and yield of oilseed rape'. (PhD Thesis, University of Nottingham).

Stehfest, E. and Bouwman, L. (2006) 'N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modelling of global annual emissions', Nutrient cycling in agroecosystems, 74(3), pp. 207-228.

Stein, L., Boulding, R., Helmick, J. and Murphy, P. (1995) 'Process design manual: land application of sewage sludge and domestic septage', Cincinnati, Ohio: US Environmental Protection Agency.

Stokes, D., Sylvester-Bradley, R., Clare, R., Scott, R., Hopkinson, J., Milford, G. and Salmon, S. (1998) 'An integrated approach to nitrogen nutrition for wheat', HGCA Project Report 159 (United Kingdom).

Storer, K., Berry, P., Kindred, D. and Sylvester-Bradley, R. (2018) 'Identifying oilseed rape varieties with high yield and low nitrogen fertiliser requirement', Field Crops Research, 225, pp. 104-116.

Strebel, O. and Duynisveld, W. H. (1989) 'Nitrogen supply to cereals and sugar beet by mass flow and diffusion on a silty loam soil', Zeitschrift für Pflanzenernährung und Bodenkunde, 152(2), pp. 135-141.

Sylvester-Bradley, R. (1992) Interpretation of crop nitrogen responses. ADAS Course Notes, Ref: SS422-25G2.

Sylvester-Bradley, R. and Makepeace, R. (1984) 'A code for stages of development in oilseed rape (*Brassica napus* L.) Aspects of applied Biology'. pp. 399-419.

Sylvester-Bradley, R., Stokes, D., Scott, R. and Clare, R. (1998) 'Canopy management in winter wheat'. University of Nottingham/ADAS Centre for Research in Agronomy, Boxworth, Cambridge, CB3 8NN (United Kingdom).

Sylvester-Bradley, R., Berry, P., Wiseman, J. and Cottrill, B. (2005) 'Yields of UK crops and livestock: physiological and technological constraints, and expectations of progress to 2050'', DEFRA Project No. IS0210. Final Report, 21.

Sylvester-Bradley, R., Kindred, D., Weightman, R., Thomas, B., Swanston, S., Thompson, D., Feuerhelm, D., Creasy, T., Argillier, O. and Melichar, J. (2010) 'Genetic reduction of energy use and emissions of nitrogen through cereal production: GREEN grain', HGCA Project Report, (468).

Sylvester-Bradley, R. and Kindred, D. R. (2009) 'Analysing nitrogen responses of cereals to prioritize routes to the improvement of nitrogen use efficiency', Journal of Experimental Botany, 60(7), pp. 1939-1951.

Sylvester-Bradley, R., Lunn, G., Foulkes, J., Shearman, V., Spink, J. and Ingram, J. (2002) 'Management strategies for high yields of cereals and oilseed rape'. HGCA Conference: Agronomic Intelligence: the basis for profitable production.

Sylvester-Bradley, R., Kindred, D., Wynn, S., Thorman, R. and Smith, K. (2014) 'Efficiencies of nitrogen fertilizers for winter cereal production, with implications for greenhouse gas intensities of grain', The Journal of Agricultural Science, 152(1), pp. 3-22.

Sylvester-Bradley, R., Kindred, D., Berry, P., Storer, K., Kendall, S. and Welham, S. (2015) 'Development of appropriate testing methodology for assessing nitrogen requirements of wheat and oilseed rape varieties', DEFRA Evidence Project Final Report.

Szot, B., Tys, J. and Bilanski, W. (1991) 'Studies of rape seed resistance to mechanical damage'. 8^{th} International Rapeseed Congress, Canada, 1251-1255.

Takashima, N. E., Rondanini, D. P., Puhl, L. E. and Miralles, D. J. (2013) 'Environmental factors affecting yield variability in spring and winter rapeseed genotypes cultivated in the south eastern Argentine Pampas', European Journal of Agronomy, 48, pp. 88-100.

Tatchell, G. M. 1977. *Oilseed rape (Brassica napus L.): pest crop relationships.* University of London.

Terry, R., Nelson, D. and Sommers, L. (1979) 'Decomposition of anaerobically digested sewage sludge as affected by soil environmental conditions', Journal of Environmental Quality, 8(3), pp. 342-347.

Ulas, A., Behrens, T., Wiesler, F. and Horst, W. J. (2015) 'Defoliation affects seed yield but not N uptake and growth rate in two oilseed rape cultivars differing in post-flowering N uptake', Field Crops Research, 179, pp. 1-5.

USDA. Oilseeds: World Markets and Trade. 2022. https://apps.fas. usda.gov/psdonline/circulars/oilseeds.pdf

Vaidyanathan, L., Sylvester-Bradley, R., Bloom, T. and Murray, A. (1987) 'Effects of previous cropping and applied nitrogen on grain nitrogen content in winter wheat', Aspects of Applied Biology, 15, pp. 227-237.

Van de Wouw, A. P., Elliott, V. L., Chang, S., López-Ruiz, F. J., Marcroft, S. J. and Idnurm, A. (2017) 'Identification of isolates of the plant pathogen Leptosphaeria maculans with resistance to the triazole fungicide fluquinconazole using a novel in planta assay', PloS one, 12(11), pp. e0188106.

Van Groenigen, J., Kasper, v. G., Velthof, G., Van den Pol-van Dasselaar, A. and Kuikman, P. (2004) 'Nitrous oxide emissions from silage maize fields under different mineral nitrogen fertilizer and slurry applications', Plant and Soil, 263(1), pp. 101-111.

Velička, R., Pupalienė, R., Butkevičienė, L. M. and Kriaučiūnienė, Z. (2011) 'The influence of sowing date on winter rape over-wintering and yield in the middle Lithuania', Journal of Food, Agriculture & Environment, 9(3/4 part 1), pp. 348-353.

Verheijen, F.G., Bellamy, P.H., Kibblewhite, M.G. and Gaunt, J.L., 2005. Organic carbon ranges in arable soils of England and Wales. *Soil Use and Management*, *21*(1), pp.2-9.

Villar, N., Aranguren, M., Castellón, A., Besga, G. and Aizpurua, A. (2019) 'Soil nitrogen dynamics during an oilseed rape (*Brassica napus* L.) growing cycle in a humid Mediterranean climate', Scientific reports, 9(1), pp. 1-13.

Vitousek, P. M., Naylor, R., Crews, T., David, M., Drinkwater, L., Holland, E., Johnes, P., Katzenberger, J., Martinelli, L. and Matson, P. (2009) 'Nutrient imbalances in agricultural development', Science, 324(5934), pp. 1519-1520.

VOß, K. (2004) 'Remote Sensing and Landscape Metrics to Identify and to Assess Site-Specific Damage in Cultivation Systems of Central Europe (Fernerkundung und Landschaftsstrukturmaße zur Beschreibung und Erfassung von teilschlagspezifischen Pflanzenschäden in landwirtschaftlichen Anbausystemen Mitteleuropas)', Erdkunde, pp. 283-289.

Genstat Software 19th Edition. Available at: https://www.vsni.co.uk/software/genstat.

Walker, K. C. and Booth, E. J. (2001) 'Agricultural aspects of rape and other Brassica products', European journal of lipid science and technology, 103(7), pp. 441-446.

Wall, D. and Plunkett, M. (2021) 'Major and micro nutrient advice for productive agricultural crops'. Teagasc Agriculture and Food Development Authority, Wexford: Ireland.

Walsh, S. (2016) 'An investigation into the factors affecting soil nitrogen supply under Irish conditions and methods that can be used to predict soil nitrogen supply'. PhD Thesis, University College Dublin, Ireland.

Wanasundara, J. P., McIntosh, T. C., Perera, S. P., Withana-Gamage, T. S. and Mitra, P. (2016) 'Canola/rapeseed protein-functionality and nutrition', OCl, 23(4), pp. D407.

Wang, C., Wan, S., Xing, X., Zhang, L. and Han, X. (2006) 'Temperature and soil moisture interactively affected soil net N mineralization in temperate grassland in Northern China', Soil Biology and Biochemistry, 38(5), pp. 1101-1110.

Wang, W., Lu, J., Ren, T., Li, X., Su, W. and Lu, M. (2012) 'Evaluating regional mean optimal nitrogen rates in combination with indigenous nitrogen supply for rice production', Field Crops Research, 137, pp. 37-48.

Wang, X., Ye, T., Ata-Ul-Karim, S. T., Zhu, Y., Liu, L., Cao, W. and Tang, L. (2017) 'Development of a critical nitrogen dilution curve based on leaf area duration in wheat', Frontiers in plant science, 8, pp. 1517.

Waring, S. and Bremner, J. (1964) 'Ammonium production in soil under waterlogged conditions as an index of nitrogen availability', Nature, 201(4922), pp. 951-952.

West, J. S., Kharbanda, P., Barbetti, M. and Fitt, B. D. (2001) 'Epidemiology and management of *Leptosphaeria maculans* (phoma stem canker) on oilseed rape in Australia, Canada and Europe', Plant Pathology, 50(1), pp. 10-27.

Weymann, W., Sieling, K. and Kage, H. (2017) 'Organ-specific approaches describing crop growth of winter oilseed rape under optimal and N-limited conditions', European Journal of Agronomy, 82, pp. 71-79.

White, C. A., Sylvester-Bradley, R. and Berry, P. M. (2015) 'Root length densities of UK wheat and oilseed rape crops with implications for water capture and yield', Journal of Experimental Botany, 66(8), pp. 2293-2303.

Wild, A. and Cameron, K. 1980. Soil nitrogen and nitrate leaching. In 'Soils and Agriculture'. (Ed. PB Tinker.) pp. 35-70. Blackwell: Oxford.

Williams, I.H., 2004. Advances in insect pest management of oilseed rape in Europe. In *Insect Pest Management* (pp. 181-208). Springer, Berlin, Heidelberg.

Wollring, J., Reusch, S. and Karlsson, C. (2001) 'Variable nitrogen application based on crop sensing', Nawozy i Nawożenie, 4 (9). pp. 79-98.

Wood, C., Reeves, D., Duffield, R. and Edmisten, K. (1992) 'Field chlorophyll measurements for evaluation of corn nitrogen status', Journal of Plant Nutrition, 15(4), pp. 487-500.

World Health Organization, (1993): Guidelines for drinking-water quality. Volume 1: recommendations, 2nd ed. https://apps.who.int/iris/handle/10665/259956.

Wright, G.C., Smith, C.J. and Woodroofe, M.R. (1988) 'the effect of irrigation and nitrogen fertilizer on rapeseed (*Brassica napes*) production in South-Eastern Australia', Irrigation Science, 9(1), pp.1-13.

Yadav, R., Tomar, S. and Sharma, U. (2002) 'Output: input ratios and apparent balances of N, P and K inputs in a rice-wheat system in North-West India', Experimental Agriculture, 38(4), pp. 457.

Yates, D. and Steven, M. (1987) 'Reflexion and absorption of solar radiation by flowering canopies of oil-seed rape (*Brassica napus* L.)', The Journal of Agricultural Science, 109(3), pp. 495-502.

Yousaf, M., Li, X., Zhang, Z., Ren, T., Cong, R., Ata-Ul-Karim, S. T., Fahad, S., Shah, A. N. and Lu, J. (2016) 'Nitrogen fertilizer management for enhancing crop productivity and nitrogen use efficiency in a rice-oilseed rape rotation system in China', Frontiers in plant science, 7, pp. 1496.

Zhao, Z., Wang, E., Wang, Z., Zang, H., Liu, Y. and Angus, J. F. (2014) 'A reappraisal of the critical nitrogen concentration of wheat and its implications on crop modelling', Field Crops Research, 164, pp. 65-73.

Zimmer, C.T., Müller, A., Heimbach, U. and Nauen, R. (2014) 'Target-site resistance to pyrethroid insecticides in German populations of the cabbage stem flea beetle, Psylliodes chrysocephala L.(Coleoptera: *Chrysomelidae*) ', Pesticide biochemistry and physiology, 108, pp.1-7.

Appendices

Appendix 1. Developing Irish CM

Year 3

Based on seed N, straw and podwall N content (kg/ha) of year 1 and year 2, a decision was made to develop Irish CM, as there was a suspect of high yield on zero-N plots in year 1 and year 2. Therefore, total N uptake on zero-N plots was reduced from CropN + SMN and values of 51.4 and 47.7 were obtained. An average extra value of 50, namely, additional available N appeared in between the time of early spring and harvest time. This extra 50 kgN was based for deciding IrishCM and added to SMN figures (equation). Also an extra 60 kg N/ha was added to apply at yellow bud.

$$\text{Nitrogen Requirement on Irish CM (kg N/ha)} = \frac{\text{Target N}\left(175\,\frac{\text{kgN}}{\text{ha}}\right) - (\text{SMN}+50+\text{cropN})}{\text{Fertilizer N recovery (0.6)}}$$

The N rate decision for Irish CM at year 3 has been calculated as 23-24 kgN/ha less than CM3.5, by the assumption that the soil N mineralization might well be happening at a later time than February which would also be comparatively more than the additional available N in UK conditions as a site-specific scale.

Appendix 2. The figures indicate the extensive vegetation appeared after winter defoliation in flowering stage (on the left), comparing to non-defoliated crops (on the right). Both on 225 kg/ha N application

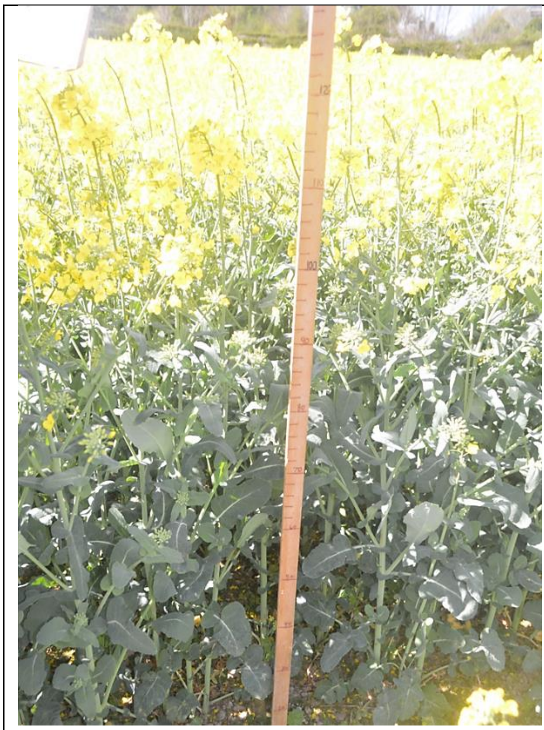
GAI (uncut) = 0.53

GAI (Cut) = 0.48

GAI as uncut

Appendix 3. Examples of approximate GAI values through online BASF website, respectively on uncut, defoliated-Rm and defoliated-Rt crops

	**N strategy= CMLo** **Sowing date= SD1** **GAI=2.5** **Height= 110-120 cm** **N rate= 56 kgM/ha**
	**N strategy= CMStd** **Sowing Date= SD1** **GAI=4.06** **Height:115-125 cm** **N rate= 140 kgN/ha**
	**N strategy= CMHiY** **Sowing Date= SD1** **GAI=4.27** **Height:110-115 cm** **N rate= 200 kgN/ha**

	**N strategy= Fix225** **Sowing Date= SD2** **GAI=4.56** **Height:120-135 cm** **N rate= 225 kgN/ha**
	**N strategy= IrishCM** **Sowing Date= SD1** **GAI=3.14** **Height:100-120 cm** **N rate= 116 kgN/ha**

Appendix 4. Examples of non-defoliated plot images in end-April 2020-21 at flowering GS, with their N strategy, GAI, height and N rate in Malones field, Oak park (2020-21/ end April)

Conference posters and oral presentations

Rahimitanha, Sh., Woodcock, T., Berry, P. and Forristal, D. Optimizing winter oilseed Rape canopy at flowering in Ireland. 15th International Rapeseed Congress. June 2019. Berlin.

Rahimitanha, Sh., Woodcock, T., Berry, P. and Forristal, D. Optimizing Oilseed Rape nitrogen management from sowing to flowering in a mild climate. National Tillage Conference, January 2020. Ireland.

Forristal D. and **Rahimitanha, Sh**. Fertilizer savings in break crops and by spreading fertilizer evenly. National Tillage conference, January 2022. Ireland (Oral presentation).

Abstract, poster and oral presentation

Rahimitanha, Sh., Woodcock, T., Berry, P. Spink, J. and Forristal, D. Optimizing Winter oilseed rape N uptake in a mild Atlantic climate. Brian Chambers Award competition, International Fertilizer Society. December 2021. Robinson College, Cambridge (Top ten candidate for the Brian Chambers Awards)

Oral Presentation in groups to bigger group of audience, advisors, stakeholders

Rahimitanha Sh. June 2019 Open day. A summary of the experimental design and preliminary results to public in collaboration with the advisors.

Forristal, D and **Rahimitanha, Sh**. June 2021 Open day. A summary of the experimental design and two years yield result, with emphasis on the possibility of the additionally available N.

Spink J. Forristal, D and **Rahimitanha Sh**. February 2022. A meeting with SeedTech company (Co.Waterford) sharing the experimental design and findings, with the emphasis on the applicability of UK-canopy management in Irish climate.

Publication

Rahimitanha, S., Woodcock, T., Spink, J., Forristal, P.D. and Berry, P.M., 2022. The Impact of Sowing Date on Soil Mineral Nitrogen Uptake Efficiency and Fertilizer N Uptake Efficiency for Winter Oilseed Rape (*Brassica napus* L.) in Ireland. *Agronomy*, *12* (7), p.1551.