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Do regenerative farming practices pave the way for UK agriculture to meet net zero?

Written by:

Chris Taylor NSch

September 2024

A NUFFIELD FARMING SCHOLARSHIPS REPORT

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"Leading positive change in agriculture. Inspiring passion and potential in people."

Title	Do regenerative farming practices pave the way for UK agriculture to meet net zero?
Scholar	Chris Taylor
Sponsor	McDonald's UK & Ireland
Objectives of Study Tour	• Meeting net zero whilst maintaining productivity and profitability on farms. • Ensuring agriculture is resilient to an ever-changing climate, full of extreme weather events. Improving organic matter (carbon) levels in our agricultural soils.
Countries Visited	Canada, USA, Brazil, France, UK, Denmark, Norway
Messages	• The best time to sample fields for organic matter was 20 years ago, the second-best time is now! • Carry out a whole farm, carbon audit to identify areas to target for mitigating greenhouse gas emissions and understand your current sequestration potential. • A transition to regenerative farming should be planned thoroughly with a phased approach that you and your business are comfortable with. • Seek guidance and advice from practitioners of regenerative farming to help implement practices that will help your business move forward in a more sustainable manner. • In selling carbon credits off the farm, ensure you're not undermining your potential to hit net zero in your own right in the future.

EXECUTIVE SUMMARY

UK agriculture is at the forefront of one of the biggest global challenges in meeting net zero by 2050. Net zero is a state in which greenhouse gases being emitted into the atmosphere are offset by removal out of the atmosphere. UK agriculture is responsible for an estimated 45 million tonnes of carbon dioxide equivalent per annum, which equates to 10% of total UK greenhouse gas emissions. Agriculture is, however, well placed as an industry to offset emissions through sequestering carbon in soils in the form of organic matter. With climate change impacts being felt in the form of extreme weather patterns, the other aspect to consider is ensuring UK farms are resilient, both financially and environmentally. Does regenerative farming provide a solution for UK farmers to meet net zero, whilst remaining profitable, enhancing the local environment and feeding a growing population?

This study was undertaken to identify the main contributing factors of greenhouse gas emissions in UK agriculture and find solutions to mitigate their impact. One of the concerns for UK agriculture is that heavy polluting industries see the sequestration potential of farms as a tool they can utilise on their own path to net zero. This includes the purchase of prime agricultural land for planting trees, renewable energy generation such as solar, or for purchasing carbon credits from farmers. For productive agriculture to remain on UK shores, whilst meeting net zero, this study focused on regenerative farming as a system to sequester carbon in the form of soil organic matter, whilst reducing emissions associated with arable production.

The initial area of interest was the USA and Canada to visit broadacre cropping farms that have been practicing regenerative farming techniques such as no-till establishment and cover cropping for decades. This was an important factor to evaluate the long-term effects of regenerative practices and learn from their experience, both positive and negative. The focus then shifted to regenerative practices in France and Scandinavia to ensure relevance to the UK in terms of soil types, cropping and climatic conditions. The outcome in visiting these countries was to gain an understanding of the innovative practices that can be implemented on UK farms to meet net zero in a holistic manner.

Meeting net zero won't be achieved via a single solution or idea but through incremental gains and an industry wide effort. For farmers, it's important to understand the carbon balance in their individual businesses, to give clarity and direction for changes to be implemented. When fully integrated into a system-based approach, regenerative agriculture offers methods of mitigating these emissions on a path to net zero. When setting net zero as a target for a business, we should not lose sight of other considerations, including environmental, economic and social benefits.

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CHAPTER 1 - PERSONAL INTRODUCTION

I grew up in South Wales, on the outskirts of the city of Newport. Having not come from a family farm, my entry into the agricultural industry was not conventional and revolved around a passion for the outdoors, a hard-work ethic and not being afraid to get my hands dirty. I have always been inquisitive, keen to further my knowledge and happy to challenge the 'status quo', not having been brought up with pre-conceptions and traditional practices from a young age.

After various weekend and summer jobs on mixed farms, I made my way to local agricultural college to study a National Diploma. This led to Harper Adams University College, where I studied a BSc Hons in Agriculture, specialising in crop production in my final year. For the work placement commitment of my degree, I spent a year working in Australia, which inspired my final year dissertation on 'The effects of controlled traffic farming practices on soil health and function'. This was the period that kick started my passion for soil health and a willingness to learn more about the world under our feet.

Post university, I have held positions at The Co-operative Farms (Farm care) as a Graduate Management Trainee and an Agronomist and Regional Technical Advisor. Since graduating from Harper Adams University College in 2012, I have been continually learning through work experience and further education courses. In 2019, I was awarded the BASIS Diploma in Agronomy with Environmental Management. In achieving this, I realised a long-term goal, which had spanned five years and an accumulation of 120 credits through a wide range of courses and disciplines.

In 2022, I was successful in my application for a Nuffield Farming Scholarship, which was a long-term ambition that goes right back to the careers fair at university in 2007. I must thank my sponsor, McDonalds UK & Ireland, for giving me the opportunity to travel and achieve this long-term goal. My final thanks must go to my wife Beth and our daughter Zara for being so supportive and understanding over the last two years, whilst I've undertaken my study.

CHAPTER 2 - BACKGROUND TO STUDY

With the urgent need to reduce greenhouse gas (GHG) emissions, farmers of the future will need to transition to a carbon neutral farming system, whilst also feeding a growing population. Climate change is a factor that is playing an ever-increasing role in our day-to-day lives and is being exacerbated by human activities. These include the burning of fossil fuels and depletion of natural capital such as the cutting down of forests, the draining of peat bogs, a worldwide loss of biodiversity and the degradation of land. The importance of reducing our carbon emissions, comes down to keeping our planet healthy and inhabited by the diversity of life.

Within the agricultural sector, net zero is a two-sided affair, as a source of emissions and sequestration. This comes with challenges and opportunities, but I personally believe, any net zero plan for the agricultural sector needs to factor in food production as the primary output. The concern for many is that farmers and prime agricultural land will be utilised for off-setting heavy carbon emitting industries on their own path to net zero. This could be via renewable energy generation, such as solar or wind, the purchase of land for planting trees and for carbon offsetting via carbon credits. We don't want to sell out our industry for the benefit of others, who change no practices but offset via carbon credits and tree planting, only for UK agriculture to fall short of the target. As custodians of the UK landscape, we are arguably one of the most important industries to get this right.

As an agronomist, I am passionate about guiding farmers and the wider industry towards net zero, with a practical approach that maintains productivity, profitability and which enhances the environment. Having spent a year working in Australia, it wasn't until many years later that I realised the impact my experience there had on me and particularly how it broadened my knowledge and challenged traditional farming practices.

In 2012, I completed my dissertation on controlled traffic farming and its effects on soil health properties, with a focus on increasing organic matter levels to improve a soils resilience and its ability to deliver profitable crops. I believe the regenerative farming movement has awakened this passion for a larger group of the agricultural industry under a different narrative. In my Nuffield study, I wanted to critique the regenerative farming movement and gain a better understanding from pioneers and practitioners about the benefits and challenges they have faced on their journey.

The aims of my Nuffield Farming Scholarship were to understand by adopting regenerative farming practices, UK agriculture could become more resilient, sustainable and environmentally sensitive, whilst remaining productive. The main drivers for my passion and research are:

- Meeting net zero whilst maintaining productivity and profitability on farms.
- Ensuring agriculture is resilient to an ever-changing climate, full of extreme weather events.
- Ensuring food production is enhancing the local environment.
- Improving organic matter (carbon) levels in our agricultural soils.
- Managing weeds, pests and diseases in a sustainable manner.
- Offering farmers an insight into what can be achieved if we're open to change.

CHAPTER 3 - MY STUDY TOUR

March 2022	**UK - Norfolk and London** The contemporary scholars conference in Norfolk and London was an opportunity to meet fellow scholars around the world and gain valuable contacts and insights into travel in their respective countries.	**2 weeks**
March 2022 – June 2023	**UK – Various** Various farmer visits, conferences and events held in the UK to ensure relevance of my experience elsewhere to UK agriculture.	**2 weeks**
July 2022	**Canada – Ontario and Alberta** Canada was an opportunity to visit large scale arable farmers and research farms, who are resilient in a climate of extremes.	**2 weeks**
July -August 2022	**USA – Iowa, Illinois, South Dakota, Philadelphia and Delaware** The USA was an insight into research farms and large-scale arable farmers who have been practicing regenerative agriculture.	**2 weeks**
August 2022	**Brazil - Sao Paulo, State of Parana and Minas Gerais** My tour in Brazil was organised by Fort Green to visit farms and research facilities throughout Southern Brazil.	**1 week**
November 2022	**France – Amiens** My First trip to France was with Cerriance, who hosted several UK farmers and agronomists on a demonstration tour of their cover crop platforms that are replicated throughout France.	**3 days**
February 2023	**France – Moulins** My second trip to France was to visit farmers who are practicing conservation agriculture and gaining an understanding of net zero ambitions in central Europe.	**1 week**
May 2023	**Norway - Oslo region** In Norway, I wanted to explore the boundaries of what is possible in northern Europe in terms of cover cropping, no-till establishment of crops and fertility building, in a high-rainfall region.	**3 days**
May 2023	**Denmark - Copenhagen region** In Denmark, I had similar outcomes to Norway but wanted to gain a better understanding of nutrient management planning and how to grow productive crops with better NUE.	**3 days**

CHAPTER 4 – NET ZERO AND CLIMATE CHANGE

Anthropogenic climate change is a reality, which we must all accept and work collaboratively towards addressing. The ambition of net zero carbon dioxide (CO_2) emissions is to limit global temperature rises to 1.5°C above pre-industrial levels by 2100. Limiting global warming to 1.5°C by 2100, requires us to meet net zero globally by 2050. In 2017, human-induced global warming surpassed 1°C above pre-industrial levels, which gives an indication of the monumental task we must undertake to limit further temperature rises by 2100. Figure 1, from the Intergovernmental Panel on Climate Change (IPCC) focuses on the observed changes in 6 key indicators of climate change from 1850 to 1950 and 1950 to 2018 respectively (Chen *et al*, 2021).

The key indicators focus on:

- CO_2 concentration
- Precipitation
- Glacier mass loss
- Global surface temperatures
- Global sea level
- Ocean heat content

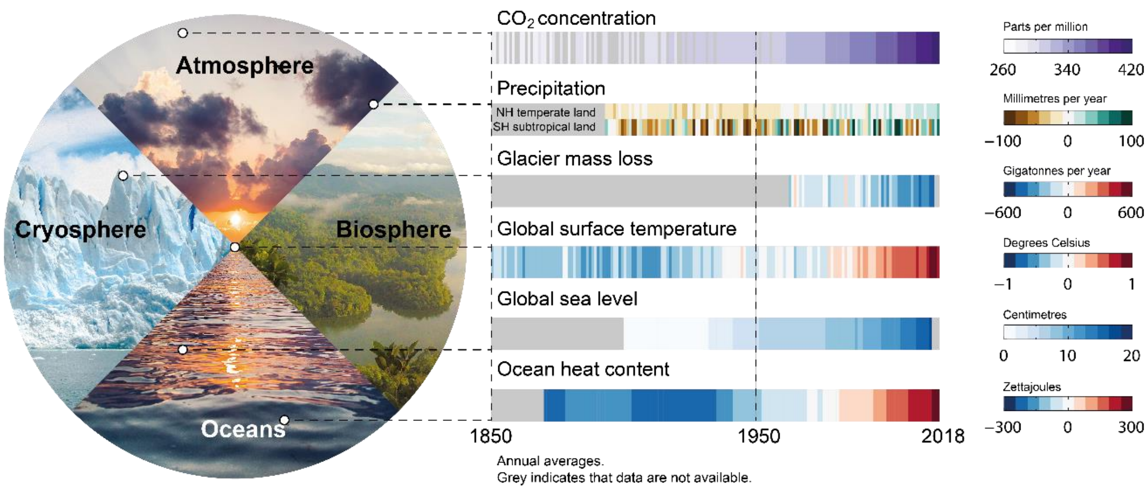

Figure 1: Changes to the climate system from 1850 to 2018. Source: IPCC, 2021

4.1 Agriculture and net zero

"Net zero is a state in which, the greenhouse gases (GHG) being emitted into the atmosphere are balanced by removal out of the atmosphere." (Net zero Climate, 2023)

The National Farmers' Union (NFU) set the ambitious goal of meeting net zero across the agricultural industry in England and Wales by 2040. Net zero is an important factor in UK agriculture as the industry can be seen as both a carbon source and carbon sink. This is down to the nature of plant growth, with CO_2 being one of the fundamental elements required during photosynthesis. The CO_2 absorbed during photosynthesis can be held in soils in the form of organic matter, acting as a carbon sink. In terms of plant growth, carbon dioxide is absorbed in abundance during the periods of rapid crop growth in the spring and summer months, bringing the overall concentrations of CO_2 in the atmosphere down (Jacobson *et al*, 2023).

"Net zero is a state in which, the greenhouse gases (GHG) being emitted into the atmosphere are balanced by removal out of the

In Figure 2, you can see that despite seasonal oscillations in atmospheric CO_2 levels, the long-term trend is increasing dramatically over time, exacerbating climate change. The following sections detail the contribution UK agriculture plays in GHG emissions.

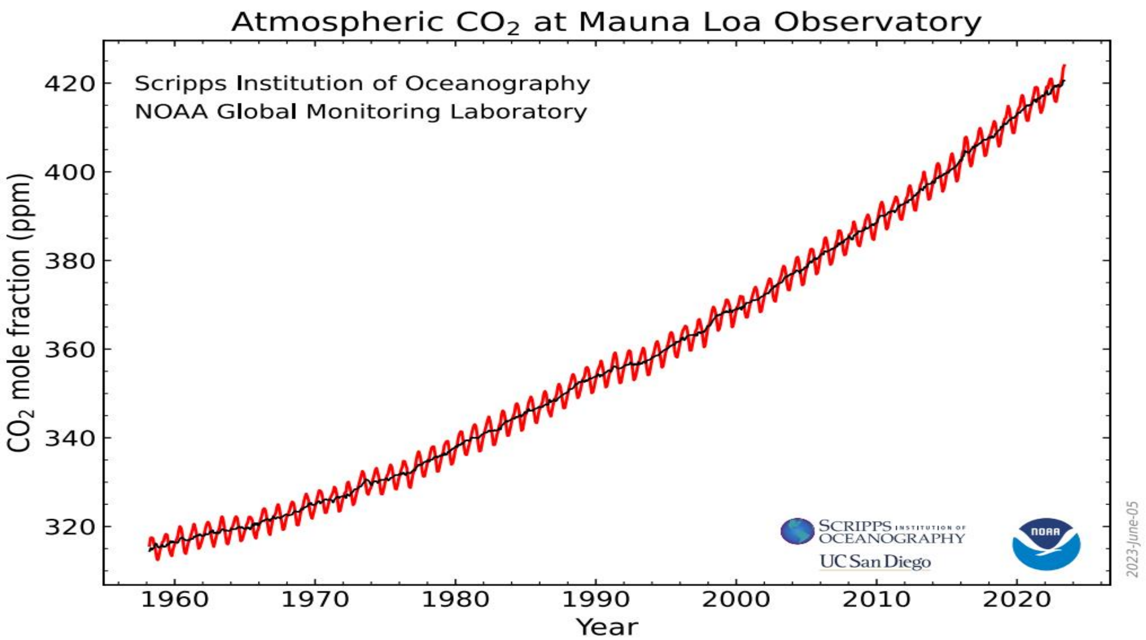

Figure 2: Shows monthly mean carbon dioxide measured at Mauna Loa Observatory, Hawaii. Source: CarbonTracker, 2022

4.2 UK agriculture - emissions factors

UK agriculture is responsible for approximately 45 million tonnes of carbon dioxide equivalents (CO_2e) per annum, which equates to 10% of total UK GHG emissions. CO_2e is the main metric in calculating emissions for carbon accounting and can be referred to as the global warming potential (GWP) of different GHGs. Agriculture is responsible for three main emissions factors in the form of CO_2, methane (CH_4) and nitrous oxide (N_2O). Within UK agriculture, estimated contributions from these GHG sources are:

- Carbon dioxide (CO2) accounts for 10% of emissions.
- Nitrous oxide (N_2O) accounts for 40% of emissions.
- Methane (CH_4) accounts for 50% of emissions.

(NFU, 2019)

Emissions from these sources are explained in more detail in the following sections, including their importance within the agricultural industry. Figure 3, from the latest IPCC report, elaborates on the main drivers, globally, of climate change including emissions from agricultural sources, such as erosion of soils, deforestation and over grazing. The UK climate has been subtly changing over the last several years, leaving UK farmers in a very risky position. With extremes of rainfall and drought being experienced in the same season for the last three years, many questions are being asked as to what constitutes 'normal' weather patterns for the UK and how can we create a resilient farming system?

Issue/ syndrome	Impact on climate change	Human driver	Climate driver	Land management options	References
Erosion of agricultural soils	Emission: CO_2, N_2O			Increase soil organic matter, no-till, perennial crops, erosion control, agroforestry, dietary change	3.1.4, 3.4.1, 3.5.2, 3.7.1, 4.8.1, 4.8.5, 4.9.2, 4.9.5
Deforestation	Emission of CO_2			Forest protection, sustainable forest management and dietary change	4.1.5, 4.5, 4.8.3, 4.8.4, 4.9.3
Forest degradation	Emission of CO_2 Reduced carbon sink			Forest protection, sustainable forest management	4.1.5, 4.5, 4.8.3, 4.8.4, 4.9.3
Overgrazing	Emission: CO_2, CH_4 Increasing albedo			Controlled grazing, rangeland management	3.1.4.2, 3.4.1, 3.6.1, 3.7.1, 4.8.1.4
Firewood and charcoal production	Emission: CO_2, CH_4 Increasing albedo			Clean cooking (health co-benefits, particularly for women and children)	3.6.3, 4.5.4, 4.8.3, 4.8.4
Increasing fire frequency and intensity	Emission: CO_2, CH_4, N_2O Emission: aerosols, increasing albedo			Fuel management, fire management	3.1.4, 3.6.1, 4.1.5, 4.8.3, Cross-Chapter Box 3 in Chp 2
Degradation of tropical peat soils	Emission: CO_2, CH_4			Peatland restoration, erosion control, regulating the use of peat soils	4.9.4
Thawing of permafrost	Emission: CO_2, CH_4			Relocation of settlement and infrastructure	4.8.5.1
Coastal erosion	Emission: CO_2, CH_4			Wetland and coastal restoration, mangrove conservation, long-term land-use planning	4 .9.6, 4.9. 7, 4.9.8
Sand and dust storms, wind erosion	Emission: aerosols			Vegetation management, afforestation, windbreaks	3.3.1, 3.4.1, 3.6.1, 3.7.1, 3.7.2
Bush encroachment	Capturing: CO_2, Decreasing albedo			Grazing land management, fire management	3.6.1.3, 3.7.3.2

Human driver	Climate driver
Grazing pressure	Warming trend
Agriculture practice	Extreme temperature
Expansion of agriculture	Drying trend
Forest clearing	Extreme rainfall
Wood fuel	Shifting rains
	Intensifying cyclones
	Sea level rise

Figure 3: Shows key desertification and land degradation issues, how they impact climate change, and the key drivers, with potential solutions. Source: IPCC, 2019.

4.2.a - Carbon dioxide (CO_2)

GHG emissions are an intangible entity, and it can be hard to envisage a tonne of emissions. CO_2e is utilised as the industry benchmark for GHG emissions with CO_2 given a GWP of one.

The Farm Carbon Toolkit (2023) states the main sources of CO_2 within agriculture are:

- Burning of fossil fuels such as diesel and petrol for transport, distribution and land work.
- Heating, power generation and drying grain using oil and natural gas.
- Land use change is one of the largest sources of CO_2 emissions worldwide. For example, draining peat soils, converting woodland to intensively farmed fields and removing natural habitats.
- Disturbing soil also releases CO_2 via regular tilling and soil compaction from heavy machinery. Adopting 'minimum tillage' and 'no-till' techniques prevents soil disturbance and dramatically reduces these emissions while improving soil structure and quality.

4.2.b - Nitrous oxide (N_2O)

N_2O, in the latest IPCC report has been given a GWP value of 265 with respect to its potency in comparison to CO_2 (Farm Carbon Toolkit, 2023). Considering N_2O accounts for 40% of total emissions from UK agriculture, this is a major factor of climate change which must be addressed.

The IPCC outlines "the main anthropogenic source of N_2O is agriculture (soil and animal manure management), but important contributions also come from sewage treatment, fossil fuel combustion, and chemical industrial processes. N_2O is also produced naturally from a wide variety of biological sources in soil and water, particularly microbial action in wet tropical forests." (IPCC, 2023).

4.2.c - Methane (CH_4)

CH_4 in the latest IPCC report has been given a GWP value of 28 with respect to its potency in comparison to CO_2 (Farm Carbon Toolkit, 2023).

In the latest IPCC report it was identified that significant CH_4 emissions occur as a result of animal husbandry and agriculture, and their management represents a major mitigation option (IPCC, 2023).

For an average UK arable farm, the breakdown of GHG emissions is displayed in Figure 4.

Source of GHG emissions	Contribution to GHG Emissions (%)
The production and application artificial nitrogen	60-70%
Fuel usage and field operations	20%
The production and application of other fertiliser inputs (lime, organic manures and P & K fertilisers)	10-15%
Seed production – growing, processing, transport etc	10%
Crop protection products (Pesticides)	1%

Figure 4: Contribution towards GHG emissions from the average UK arable farm. Source: Farm Carbon Toolkit, 2023

4.3 - Net zero in practice

Taking into consideration, the insights into emissions from the previous Chapter, I consider net zero on farms as a savings account, with carbon inputs acting as payments into the savings account and carbon emissions acting as withdrawals from the account. A lot of the focus has been placed on increasing carbon sequestration into soils which has prompted no-till establishment of crops, cover cropping, tree planting, return of crop residues to fields and increasing organic matter levels in soils. Conversely, identifying and addressing the largest emissions factors that are occurring in a farming business is an important first step to take. Once identified, changes or improvements to the farming system can dramatically reduce the emissions factors on an overall carbon balance.

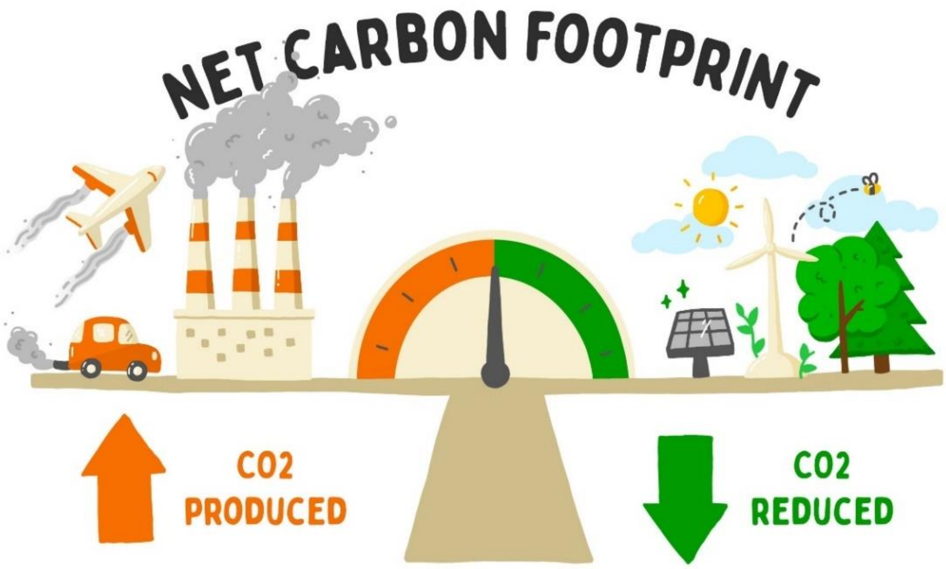

Figure 5: Net Carbon Footprint. Source: Tee Public, 2023

If meeting net zero on an individual farm is balancing the carbon emissions with carbon sequestration to achieve carbon neutrality, then for UK agriculture to meet net zero, it is likely going to be a combined, industry wide effort. This is due to the potency of methane (GWP of 28) and nitrous oxide (GWP of 265) emissions as described in detail previously and their embedded nature in certain farm businesses, particularly those with intensive livestock enterprises.

4.3 - Chapter conclusions

- UK agriculture is responsible for approximately 10% of UK GHG emissions.
- As an industry, agriculture can remove CO_2 from the atmosphere and store it in soils.
- Approximately 90% of GHG emissions on UK arable farms are associated with the production and application of nitrogen fertilisers, fuel usage and field work.
- Meeting net zero as an industry will be a balance of reducing GHG emissions, whilst sequestering carbon on our farms.

CHAPTER 5 - WHAT IS REGENERATIVE AGRICULTURE?

Regenerative agriculture is a farming system, based around five principles of land management. The five principles, as demonstrated in Figure 6, are:

- Minimise soil disturbance where possible.
- Keeping the soil surface covered as often as possible.
- Maintain living roots in the soil as often as possible.
- Grow a diverse range of crops.
- Integrate livestock where possible.

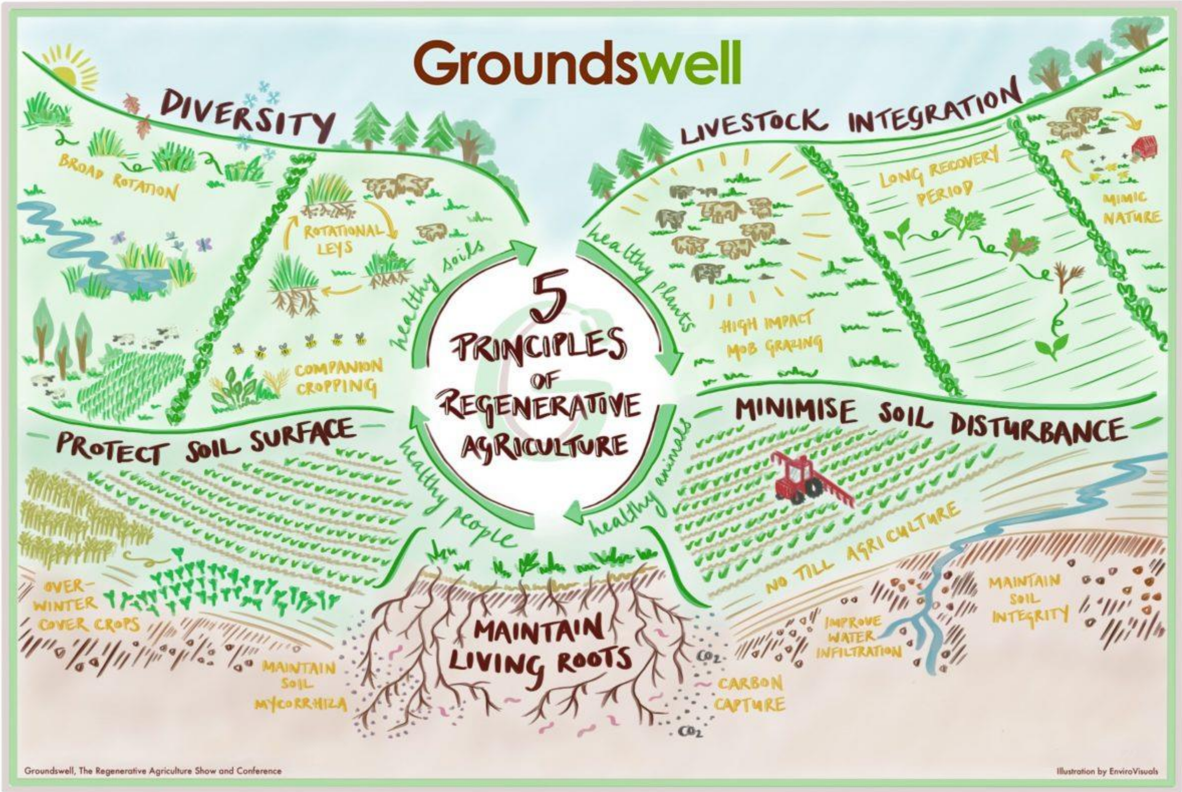

Figure 6: The five principles of regenerative agriculture. Source: Groundswell Ag, 2023

As regenerative agriculture is based on principles that have been proven to build organic matter levels, improve soil resilience, reduce fuel usage and other input requirements, it appeared to be the perfect farming system to reach net zero for UK agriculture. I based my Nuffield Farming study on answering five key questions I had regarding a path to net zero with our current UK models:

- What do organic matter levels on the farm look like compared to local base levels?
- How has the adoption of regenerative agriculture affected your production and profitability?
- What have been your key learnings when adopting such as a system?
- What have been the challenges along the way?
- Does the adoption of regenerative agriculture help you reach net zero?

5.1 - Regenerative agriculture – principles in practice

A fully integrated regenerative farming system makes it impossible to separate the principles out into their constituent parts as they are entwined as one. This I feel best encompasses what regenerative farming is and, in these examples, genuine progress had been realised building a more resilient and sustainable farming system.

In the following chapters I have given examples of where I witnessed regenerative practices with insights into productivity, profitability, effects on organic matter and other associated benefits.

5.1.a - Keep the soil covered

In keeping the soil covered with crop residue, over time, this can alleviate the harmful effects of adverse weather, by acting as 'soil armour'. In practice, this cushions the effects of heavy rainfall, leading to more open soil structure without the risk of soil 'capping'. There are other benefits such as reduced evapotranspiration, protection from wind erosion and reduced weed pressure.

The residue management I observed at the Dakota Lakes Research Farm, paid particular attention to carbon to nitrogen ratios and how they can be manipulated to fulfil a desired outcome. This was a fascinating insight; a trial of continuous no-till corn that had run since 1990 yielded the highest organic matter levels on the farm along with the best surface retention of crop residue. With long term no-till establishment of combinable crops and residues being returned to the soil, the organic matter levels ranged from 3.5 to 5.5%. The higher end of the scale being recorded where the 30 year, no-till, continuous corn trial was held.

This example was a great insight into how rotations can be manipulated to generate or reduce crop residues, benefiting the following crop.

Figure 7: A field of wheat being harvested with a stripper header in South Dakota. Source: Author's own

5.1.b – Minimise soil disturbance

The minimising of soil disturbance is perhaps the most widely accepted and practiced principle of regenerative agriculture. It has been widely utilised as a method of reducing establishment costs, improving water infiltration, increasing organic matter levels, helping with water conservation and creating more resilient soil structure. This principle has the biggest impact on soil fauna and particularly indicator species such as earthworms.

Dale Launstein, who farms in Holland, Iowa, was an example where his journey to no-till corn and beans had seen the farm business 'convert' to no-till via an eight-year transition period through strip till. He suggested the fuel saving advantages of going to no-till as being in the region of one US gallon per acre (3.78 litres per acre or 10 L/ha) in comparison to strip-till throughout the growing season. On his 3,000-acre farm, this equated to a saving in fuel alone of $12,000 per annum. On Dale's silt loam farm, his average organic matter levels were 3.5 – 5% and he suggested the local area average was at 2%, with a lot of local farmers still cultivating soils and not cover cropping over winter.

In hearing Dale describe his 'journey' through an eight-year period of strip till, before finally moving to no-till, it highlighted the importance of 'earning the right' to farm in this manner. As stated previously, with fuel and field operations contributing circa 20% to overall emissions, the saving in fuel is an important contributor to reaching net zero. There is, however, planning, effort and resources that must go into profitably moving to no-till, with particular attention paid to detail to avoid compaction and retain a good soil structure which supports healthy plant growth.

Figure 8: Dale Launsten and author in front of a field of no-till corn, Iowa. Source: Author's own

5.1.c – Maintenance of living roots

To maintain living roots in the soil is to feed the soil food web and particularly the mycorrhizal fungi populations with a carbon source. These living roots release exudates into the soil, which help maintain a healthy, functioning soil to support plant growth. Achieving year round cover also ensures maximum sunlight interception, particularly post-harvest during the long days of summer, where photosynthesis can still function on cover or catch crops.

Woody and Catherine Van Arkel in Ontario are real pioneers who under-sow various crops with living mulches of clover species. The clover understory reduced the nitrogen requirement throughout the rotation, ensured living roots were in the ground all year round and gave ground cover to capture sunlight through the summer months post-harvest. Through a combination of no-till, cover cropping and a diverse rotation, they have achieved organic matter levels on their farm of 2.5 to 4.5%.

Frederik Larsen in Denmark operates a similar approach with lucerne, established with winter oilseed rape. The lucerne as an understory is cut over the summer months for animal feed, before the autumn crop is established, keeping the understory alive. It is hoped the living mulch will survive and feature in the rotation for several years. This type of approach isn't without its challenges, but Frederik believes this living mulch can replace the need for cover cropping on his farm over time. He will retain the associated benefits of cover crops but with one seed purchase, one establishment cost and year-round soil cover.

Figure 9: A clover understory with wheat in Norway. Source: Author's own

5.1.d – Diversity

Diversity is important for the soil food web, the interactions of roots and the sharing of resources within the soil microbiome. Diversity of cropping can take place either in space and/or time. A diverse cropping rotation, occurring over time, allows for functional benefits such as different rooting profiles, different macro and micronutrient requirements and soil structure benefits. Examples of diversity in space were outlined previously with Woody and Frederik. Other methods of diverse cropping in space would be a multispecies ley or a mixed species cover crop.

There were many examples of diversity in rotations and cover cropping during my travels but one of the countries that was very impressive for their planning and foresight was Norway. A great term I came across there was 'forgøde' which referred to the attributes or quality of the preceding crop in a rotation. The focus over the rotation would change with the needs of the individual crop but generally desirable attributes we're based around carbon: nitrogen ratios, residue management, the effect on soil friability, disease carry over, structural effects of rooting and nutrient availability to name a few. This is what diversity brings to a rotation, either in time or space.

Figure 10: A diverse cover crop being grown in Canada. Source: Author's own

5.1.e – Integration of livestock

Livestock inclusion relates well to diversity, particularly in the cycling of nutrients and the array of food sources the soil food web can draw upon. Livestock are considered an integral part of circular farming and mutual benefits and synergies can be realised for all enterprises involved in the farming system. The option to graze crops, cover crops and include perennial plants in the rotation is not to be overlooked and the ability to improve fertility and organic matter is integral.

Jamie and Ian Sculthorpe, we're a fantastic example of fertility building in an organic system, as demonstrated in Figure 9. They utilise a mixed species herbal ley for four to five years of fertility building prior to entering back into a combinable crop rotation featuring cereals, soybeans and corn. They rotationally ploughed two years in seven and had pushed organic matter levels up to 4% across the farm.

The integration of livestock can be a hard aspect for arable farmers to invest in, it requires capital expenditure in stock, fencing and equipment and the skills that come with livestock management. If livestock farming isn't for you, then this is a perfect scenario for bringing the benefits of livestock into your farm business, through a partnership. Whether this be 'tack sheep' on cover crops and winter cereals or giving a keen young farmer an opportunity to partner with you. There are endless individual circumstances here but also a lot of opportunities to explore if you're receptive to change.

Figure 11: Cattle grazing on an organic herbal ley for fertility building. Source: Author's own

5.2 – Regenerative agriculture as a farming system

To put into context regenerative agriculture as a farming system, I visited the 'home of regenerative agriculture' at Dakota Lakes Research Farm. Sam Ireland hosted me and explained the research farm, established in 1983, was to support local farmers with knowledge exchange.

The farm has been long-term no-till, with a focus towards enhanced soil and water conservation. The farm is aiming to be 'fossil fuel free' by 2026 by pressing all the oilseeds grown on the farm to be utilised as biodiesel.

The soils on the farm were subjected to a simulation of 10" of rainfall per hour without any runoff occurring.

Figure 12: An example of residue levels in the continuous corn trial at Dakota Lakes Research Farm. Source: Author's own

The region is reliant on capturing snowmelt over the winter months and conserving that for the growing crop throughout the dry spring and summer. Irrigation was available on a proportion of the farm and Sam explained how the soils on the farm had become more resilient to high rainfall weather events. In an experiment with Cornell University, the soils on the farm were subjected to a simulation of 10" of rainfall per hour without any runoff occurring. This high infiltration rate was attributed to a combination of long term no-till, keeping the soil covered and maintaining living roots.

An example of the 2022 rotation trial is in Figure 13, along with the pros and cons of each system. Sam explained the farms ambition is to maintain a minimum of 75% high residue crops in the rotation, which is possible on both the dryland and irrigated areas of the farm, but not without its challenges. The maintenance of high residue levels such as in Figure 10, was said to reduce wind erosion issues, maintain moisture levels through a reduction in evapotranspiration, increases organic matter and reduce weed seed germination. Livestock is now incorporated into the rotation, and this has allowed the farm to integrate perennial crops into the system, which has broadened their approach to residue management, particularly on the dryland area of the farm.

Dryland		
67% High residue	**67% High residue + Perennial**	**80% High residue**
Wheat Corn Broadleaf (peas, flax or canola) Wheat Sorghum Broadleaf (pea, flax or canola)	15 years of annual crops based on the previous combinable crop rotation. 5 years perennial crops focusing on switchgrass or alfalfa (lucerne)	Wheat Wheat Sorghum Corn Broadleaf (pea, flax, canola)
Pros: High diversity with several broadleaf crop options	Pros: High diversity and high residue levels. Deep perennial roots draw up nutrients	Pros: High diversity and high residue
Cons: Moderate residue	Cons: Need livestock incorporation	Cons: Lack of broadleaf may limit income potential
Irrigated		
50% High residue	**60% High residue**	**75% High residue**
Corn Soybean Corn Soybean	Corn Corn Broadleaf (Sunflowers/Soybean) Wheat – fb cover crop Broadleaf (Sunflowers/Soybean)	Corn Corn Soyabean Wheat – fb cover crop
Pros: better yield than continuous corn	Pros: Good diversity, rotation discourages pest and disease build up	Pros: High residue, diversity improves yield and discourages pests
Cons: Low residue causes soil degradation and pest problems can occur with tight rotation	Cons: Not enough high residue crops will likely degrade soils	Cons: The second-year corn yield is poor
75% High residue + Perennial		**100% High residue**
8 years of annual crops based on the previous combinable crop rotation. 4 years perennial crops focusing on alfalfa & orchard grass		Continuous corn
Pros: Very high residue production, diversity improves yields and discourages pests. Deep perennial roots draw up nutrients.		Pros: High residue
Cons: The second-year corn yield is poor		Cons: Pest problems, low diversity and low yield

Figure 13: An example of the rotation trial at Dakota Lakes Research Farm. Source: Authors own

5.3 - Chapter conclusions

- When implemented correctly, in a full system approach, regenerative agriculture principles are hard to pull apart as they intertwine and complement one another.
- You must earn the right to reach certain goals, such as no-till establishment, through a transition period that is thoroughly planned.
- The key to storing more carbon in soils in the form of organic matter comes back to carbon: nitrogen ratios and can be heavily influenced by crop residues, organic manures and cover cropping.
- Regenerative agriculture offers wide ranging benefits including profitability, productivity, resilience and improvements in soil organic matter levels.

CHAPTER 6 – INNOVATIVE SOLUTIONS

6.1 - Lessons from the organic sector

Considering regenerative agriculture as a complete systems approach to farming, I wanted to better understand the management of weeds, pests and diseases, with no artificial inputs. The drivers for addressing artificial inputs were cost inflation, loss of active ingredients and resistance issues, such as we experience with blackgrass and cabbage stem flea beetle.

For me to fully understand and address the implementation of cultural control measures, I turned to the organic sector. John Pawsey of Shimpling Park, Suffolk, declares "organic farming in its nature must be regenerative to survive in the absence of artificial inputs." During a visit to his farm it was fascinating to hear how the organic sector builds fertility, and a long-term view of farming must be considered with an outcome-based strategy in place. John has pushed the farm's average organic matter levels to 5.5%, with the local average around 3-3.5%.

Upon visiting several organic farmers across the northern hemisphere, I gained a greater appreciation for the innovation and solutions that are implemented in the organic sector.

6.1.a - Rotational no-till organic farming

A standout visit was to the Allison Organic Research Farm, where I was hosted by Dr Joel Gruver. The 75-acre research farm has been organic since 2009 and Dr Gruver explained the approach on the farm to reduce weeds, fix nitrogen and grow profitable crops.

Figure 14: Dr Joel Gruver and author in front of a 10-way cover crop mixture. Source: Author's own

The highlight of this visit was the insight into growing organic no-till soybeans, which stood out as one of the cleanest crops I had seen on my travels. The key to this was an overwinter cover crop of cereal rye, which was crimper rolled in the spring, before no-till establishment of the soya beans into the rye. The rye acted as a nutrient capturing crop over the winter and stabilised the soil before becoming a weed suppressing mat under the soya beans, utilising several of the regenerative farming principles.

The cereal rye cover crop saved three passes with a rotary hoe and two passes with a tined hoe, by suppressing weeds rather than having to remove them from the soybean crop. The other benefit of the cereal rye was that the pod set was higher on the soya beans, making harvest easier and reducing cutter bar losses from low lying pods. Organic no-till farming is always hailed as the 'holy grail' and Dr Gruver was able to demonstrate how this is possible, at least rotationally in an organic system.

Figure 15: A crop of no-till organic soybeans, growing through a crimped rye cover crop. Source: Author's own

6.2 Peer to peer learning

In Delaware, the Sussex Conservation District were supporting local growers with voluntary conservation practices based on local needs. They had several 'soil health champions' who offered peer-to-peer learning and advice based around conservation practices such as no-till establishment of crops, cover cropping and buffer strips. From long-term experience, the benefits of cover cropping were outlined as improvements in the following areas:

- Overall soil health and structural benefits.
- Reduction in erosion from wind.
- Reduction in erosion from water.
- Nutrient cycling benefits.
- Improved local water quality due to less sediment and nutrient run off.

They had a local initiative called 'Caffeine and cover crops' which were drop-in sessions run regularly to support the local uptake of cover cropping in their region.

Figure 16: Sussex Conservation District, Delaware. Source: Author's own

6.3 - Chapter conclusions

- Innovation in agriculture is constant and we need to break down barriers in a collaborative effort to reach net zero as an industry, regardless of our chosen farming system.
- Peer to peer learning offers farmers access to practitioners and pioneers who can help implement more sustainable practices on their farm businesses.

CHAPTER 7 – EMISSIONS: TACKLING THE BIG THREE!

As previously stated, the three main drivers of emissions on the average UK arable farm are fertiliser, fuel and field operations. I wanted to highlight areas of interest and particular case studies that I experienced as part of my study that gave me an insight into how these three drivers can be mitigated with regenerative farming practices.

7.1 - Fertility

With the production and application of nitrogen fertilisers equating to 60-70% of emissions for the average UK arable farm, this is the biggest area to influence. During my studies, there were numerous ways to fertilise crops but there wasn't one 'silver bullet' to such a challenging problem. I did, however, manage to glean examples where people had dramatically reduced their reliance on artificial nitrogen through fertility building prior to cash crops. The importance of carbon: nitrogen ratios were highlighted to me during my study, and I was keen to build further on this topic and understand how nutrients cycled and became crop available following a low carbon: nitrogen ratio crop, cover crop or companion crop.

> The production and application of nitrogen fertilisers equates to 60-70% of emissions for the average UK arable farm.

In central France, I heard about the inclusion of pulses in rotations prior to oilseed rape, which helped reduced the effects of cabbage stem flea beetle, but which also reduced the overall nitrogen requirement by two thirds, equating to a saving of 100 units of nitrogen (125 kg/ha N).

Rotation planning such as this offers a quantifiable solution to reducing nitrogen requirements by situating a fertility building break crop prior to nitrogen hungry cash crops. Members of the organic sector took this practice one step further and would utilise a fertility building phase prior to a hungry cash crop, in the absence of artificial inputs. This could revolve around multi species cover crops, grown in sequence over a year or two, prior to a cash crop. The most common method of building fertility was to incorporate a period of lucerne into a rotation, which was cut or grazed to feed livestock. When it was terminated prior to a cash crop, huge quantities of nitrogen were ready to feed the following crop, including winter cereals or maize.

In France, I met Ghislain who farmed 180 ha, 100 ha conventionally and 80 ha under organic certification. He explained that he was required to test his soils for soil mineral nitrogen (SMN) and would be restricted on nitrogen usage, dependant on the results.

The soil was tested in three increments, from 0-90cm in total and following a lucerne crop, the result was 300 units of nitrogen (375 kg/ha of nitrogen). Enough to comfortably grow a high yielding winter wheat crop without any requirement for artificial N, should this nitrogen be crop available.

7.2 - Fuel and field operations

In France, I visited several farmers who have been practicing rotational no-till, combined with strip till, particularly where sugar beet and oilseed rape were present in the rotation. Not only had they seen improvements in organic matter levels, reaching farm averages in the region of 3-4%, with the local average of 1.5-2%. Almost all agreed that under no-till establishment, their organic matter levels were rising on average by 0.1% per year, which they had the long-term data to prove. They remarked that their yields were the same as their neighbours, but they were spending significantly less and therefore margins were improved on their operations.

Near Moulins I met Jean Bruno (JB), who farmed himself but also contract farmed for several landlords. This gave him great insight into land that had been farmed with regenerative practices, compared to the local standard. Some of the stark messages came from establishment costs for direct drilling versus a plough and combination drill. Fuel usage was also recorded, as was his timeliness of operations. JB was very passionate about direct drilling but had to operate under the guidance of his contact farming customers, which often were at opposing ends of farming systems.

Figure 17: A field of two halves in Central France. Overwinter ploughing to the left and no-till wheat post sunflowers to the right. Source: Author's own

Considering this example, Figure 18 next is a table of establishment costs and fuel usage JB had accrued over several years of running these two systems literally side by side. With this operation running over 400ha, the savings in establishment cost, time and fuel are substantial. Taking fuel as one of the big drivers in a carbon audit, a 15,000L saving in crop establishment alone, is a significant figure. The cost saving associated with the direct drilling establishment goes a long way towards the investment of a suitable drill, which isn't considering many of the other associated benefits.

Establishment Method	Overall Cost (€/ha)	Fuel usage (L/ha)	Timeliness
Direct drill (John Deere 750a)	80	7	Excellent
Plough and combination drill	180	45	Poor
Direct drill	**Cost Saving in Total (€)**	**Fuel saving (L)**	**Time Saving**
On 400ha of arable cropping	€40,000	15,200	Priceless!

Figure 18: A table comparing crop establishment costings from Central France. Source: Author's own

Figure 19: Two no-till wheat fields under JB's management in France. Source: Author's own

7.3 - Chapter conclusions

- Striving for net zero doesn't initiate yield penalties and extra costs if implemented correctly.
- In addressing the three biggest contributors to GHG emissions with regenerative farming practices, cost savings can be realised in conjunction with multiple other associated benefits.
- The understanding and manipulation of carbon: nitrogen ratios plays a major factor in building and releasing fertility to crops to reduce our reliance on artificial fertiliser.

CHAPTER 8 - DRIVERS OF SEQUESTRATION

One of the main drivers for sequestration in carbon audits revolves around changes in organic matter levels over time. This allows a calculation to be made on the storage capacity of a soil to hold onto carbon. Work completed by the Farm Carbon Toolkit (2023) has demonstrated that every hectare of land that raises its soil organic matter levels by just 0.1% can sequester approximately 8.9 tonnes of CO_2e per year (at 1.4 g/cm^3 bulk density). Soil type, geography, rainfall, cropping and the addition of organic amendments are factors which are going to influence organic matter levels on farms.

As part of my study, I wanted to understand the main drivers and methods for increasing soil organic matter and get an appreciation for what farmers had achieved over local 'base' levels; both were of importance to my research.

> Every hectare of land that raises its soil organic matter levels by just 0.1% can sequester approximately 8.9

8.1 - Organic matter

One of my first insights was that organic matter, although considered very important to a farms resilience and for reaching net zero, was more of a longer-term goal for most farmers and usually outweighed by more pressing priorities.

In Southern Alberta, I met Harold Perry who discussed some of the 'soft benefits' of regenerative agriculture. Harold explained it wasn't always tangible benefits from a gross margin aspect that were realised over time. Wind erosion was a big problem for soil health and land degradation in Southern Alberta and by ensuring ground cover with living mulches, cover crops and the return of crop residues to fields, he believed this was a huge benefit to the farming system. Compost was utilised rotationally to improve soil biology and resilience as well as providing nutrients for growing crops. An outcome of this resilient farming business is that Harold has seen his organic matter levels on the farm reach a range between 2-3% on a light, sandy loam soil.

In Canada, Mark and Sandi Brock of Shepherds Creek Farm, Southern Ontario, spoke about resilience in farming on their land with the aim to leave the farm in better condition for the next generation. Mark suggested regenerative agriculture is not being widely adopted as a term in Canada and his view was, we should be focusing on carbon emissions, particularly fertiliser and gas used for drying crops in Canada, and how they can be reduced. With no-till, cover cropping and applications of organic manure applied rotationally, their organic matter levels ranged between 3.5 and 4% across the farm.

8.2 – Agroforestry

Agroforestry was a term I was familiar with but had never experienced in practice. During my travels I visited several farmers who had integrated agroforestry into their businesses. Tree planting provides a solution to sequestering more carbon on farms but can take prime agricultural land out of production. Planting trees on wide strips, to accommodate arable machinery or livestock in between gangways, offered a great synergy and an example of 'land sharing' techniques for reaching net zero.

Richard Thomas of Risbury Court Farm, Herefordshire explained the output of his agroforestry, integrated into permanent pasture, as being fruit, fence posts and firewood. The benefits of agroforestry to his livestock enterprise were:

- Shade
- Shelter
- A habitat for biodiversity
- Improved water holding capacity of the field

A synergistic approach to a 12-acre field, which saw 0.5 acres devoted to trees, which Richard believed would yield a higher overall production through multiple, stacked enterprises.

Figure 20: A recently established Agroforestry site in Northern France. Source: Author's own

CHAPTER 9 - DISCUSSION

With carbon emissions so hard to tangibly comprehend and visualise, it decouples the emotion and responsibility for tackling these emissions. This made my study to better understand emissions and sequestration factors on farm a difficult and multifaceted task. When attending the Oxford Farming Conference in January 2023, a quote from Jojo Mehta "The hole is in your end of the boat" re-framed for me our collective journey to net zero. When considering the monumental, global challenge to limit GHG emissions into the atmosphere, a culture of nonchalance and apportioning the blame elsewhere isn't acceptable.

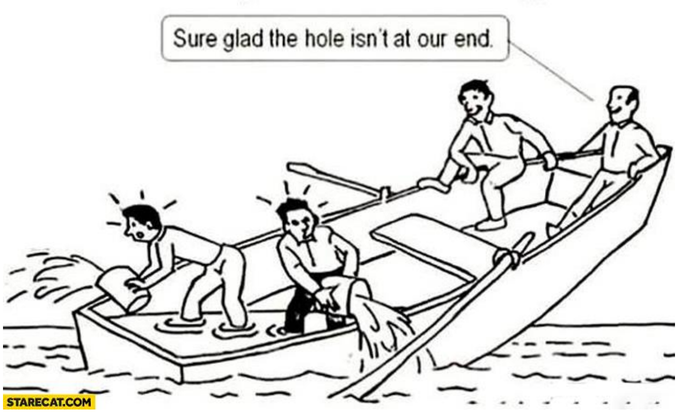

Figure 21: A visualisation of JoJo Mehat's quote "The hole is in your end of the boat". Source: Greenberg, 2017

The UK agricultural industry must accept the responsibility of reaching net zero and understand its importance in addressing anthropogenic climate change. However, when focusing on net zero as an overall goal, it's important to consider other aspects such as economic, environmental and social responsibilities. There is a term known as carbon tunnel vision, where we lose sight of the other benefits that reaching et zero could provide. The outcome of carbon tunnel vision was described in Chapter 2, where farmers utilise prime agricultural land for off-setting heavy carbon emitting industries on their own path to net zero, with schemes such as widescale tree planting.

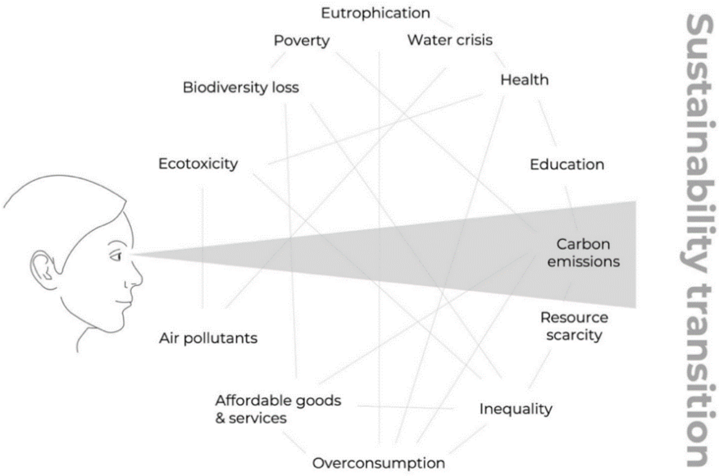

Figure 22: An illustration of carbon tunnel vision. Source: Stockholm Environment Institute, 2022

UK farming is so diverse and multifaceted that there is no blueprint for reaching net zero and each business will need to address their own individual circumstances and nuances. In considering net zero for your business, the thought process and path must be one of a long-term view, which requires stability in production and profitability. This is where, from my studies, I believe regenerative agriculture supports and complements a journey to net zero for the agricultural industry. By implementing regenerative practices, such as no-till establishment of crops and keeping the ground covered, there are wider benefits both economically and environmentally, to be realised on the path to net zero. Examples of these benefits include reduced erosion risk, better water holding capacity of soils, the capturing of nutrients leading to reduced risk of eutrophication, reduced input costs and better farm resilience.

One challenge to address is that I often find people claiming to be regeneratively farming when they are, in fact. practicing one or two principles in their farming operation. This can be misleading and undermine the movement and credibility of regenerative agriculture. During my studies, I came across examples of the five principles being utilised, whereby it was hard to separate them out to their constituent parts. Institutes such as the Dakota Lakes Research Farm and the Allison Organic Research Farm are two great examples of a systems approach to agriculture where tangible benefits of practices can be evaluated and realised over time. These are the examples I feel best encompass what regenerative farming is and, in these cases, genuine progress had been realised building a more resilient and sustainable farming system. These examples should give us the confidence and belief that farming regeneratively can create a win-win scenario for farmers, the local environment and our combined global challenge of reaching net zero.

UK agricultural has a paramount opportunity to contribute to the UK reaching its net zero obligations by transitioning to a carbon neutral farming system, whilst also feeding a growing population. Reaching net zero, won't be realised through a single idea or solution but rather a combination of factors to reach the intended goal. Although we have a good understanding of the main drivers of emissions and sequestration on farm, I believe further refinement in measurement and validation is required to improve accuracy and credibility of carbon audits. For anyone with an ambition to reach net zero, the first step is to measure your current carbon balance in relation to emissions and sequestration factors. Considering these audits will continue to develop and evolve over time, operating under the best practice and guidance we have currently allows you to be informed and driving change within the industry.

CHAPTER 10 - CONCLUSIONS

- Addressing climate change and tackling greenhouse gas emissions is imperative for keeping our planet healthy and inhabited by the diversity of life.
- Meeting net zero in UK agriculture isn't going to be realised by one large innovative idea or solution. It will be a lot of incremental gains, that amount to realising the overall goal.
- Regenerative agriculture principles should be fully integrated into a farming system, as these principles don't fulfil their potential used in isolation.
- In tackling the two big emissions factors on farms (fuel and fertiliser), regenerative agriculture provides solutions to mitigate their impact and offset through sequestration.
- When implemented correctly, regenerative agriculture offers wide ranging benefits including profitability, productivity, resilience and environmental gains.

CHAPTER 11 – RECOMMENDATIONS

Farmers

- The best time to sample fields for organic matter was 20 years ago, the second-best time is now!
- Carry out a whole farm, carbon audit to identify areas to target for mitigating greenhouse gas emissions and understand your current sequestration potential.
- A transition to regenerative farming should be planned thoroughly with a phased approach that you and your business are comfortable with.
- Seek guidance and advice from practitioners of regenerative farming to help implement practices that will help your business move forward in a more sustainable manner.
- In selling carbon credits off the farm, ensure you're not undermining your potential to hit Net Zero in your own right in the future.

Industry Body

- Ensure metrics for measuring carbon sequestered on farms are fit for the future.
- Develop an industrywide standard for the sampling of soils for the purpose of a carbon audit so results are valuable and reliable.
- Ensure schemes that are implemented to support farmers don't disadvantage early adopters of sustainable practices.
- Don't offshore our responsibilities and put UK agriculture and food security at risk.

CHAPTER 12 - POST STUDY TOUR

A Nuffield Farming Scholarship has been a dream of mine for over fifteen years now and I can honestly say it has surpassed all my expectations. During the last two years the experience has pushed me out of my comfort zone and challenged me on multiple levels. I have had the opportunity to meet and spend time with incredible pioneers and infectiously passionate people around the world which have boosted my own confidence and motivation.

My Nuffield experience highlighted to me the importance of stepping back from your day-to-day job and re-evaluating some of the larger problems in the industry. I find that by re-framing what we're trying to achieve, which is often a difficult problem, that small management steps, implemented over time can yield a big difference.

As an agronomist, it's easy to address the same problems on farm, year after year. I have often thought of this issue as a roundabout, whereby endemic problems arise yearly, we run the farming calendar and get back to the same conversation a year later, having not got off the 'roundabout'. This can be a very demoralising and frustrating process for all involved, until you start to re-frame, re-evaluate and do things differently. I believe through regenerative farming, many in the industry are transitioning towards what can be described as a carpark up ramp, which still involves travelling cyclically with the farming calendar, but at least it's on an upwards trajectory and making progress on some of the challenging problems.

I believe regenerative agriculture can offer us management solutions under a farming system that propels our trajectory on the car park up ramp, paving a way for farmers who adopt, to reach net zero. I have continued to work with farmers and businesses on transitioning into a regenerative farming system, alongside research and development (R&D) within agronomy.

Chris Taylor, 2023

CHAPTER 13 – ACKNOWLEDGEMENT AND THANKS

I would firstly like to thank my wife, Bethan, for supporting and enabling me to travel for eight weeks in the fulfilment of my study topic. Her encouragement and support have been boundless, and I feel grateful to have completed my scholarship amidst the challenges of raising a young family.

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Thirdly, I would like to thank all the people around the world, who generously gave their time, shared their knowledge and provided onward connections. The hospitality and generosity I experienced on my journey was incredible and I will be forever grateful to those that hosted me as one of their own.

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