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Fertiliser reduction: A road map for UK dairy.

Written by:

Gary Thompson NSch

April 2025

A NUFFIELD FARMING SCHOLARSHIPS REPORT

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Date of report: April 2025

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

Title	Fertiliser reduction: A road map for UK dairy.
Scholar	Gary Thompson
Sponsor	Thomas Henry Foundation
Objectives of Study Tour	Finding solutions to reduce dairy farming's reliance on chemical fertilisers derived from mined minerals and fossil fuels. Solutions must be economically viable for all sizes of dairy farmers not just the largest.
Countries Visited	United Kingdom, Ireland, USA, Netherlands, Germany and Denmark.
Messages	1. Nutrient accounting: A centralised system would limit administration, increase accuracy and develop understanding of nutrient flows, changing farmer behaviour. 2. Circular nutrients: Recycling excess nutrients, diffusely contained in low dry matter slurries back to crop growers, is practically and economically challenging. Anaerobic digestion provides an economic solution. 3. Ryegrass breeding: Adopting a wider, balanced approach to recommended list criteria, could help prevent nutrient loss in several ways.

EXECUTIVE SUMMARY

Half of global food production relies on synthetic fertiliser manufactured from natural gas and other mined natural resources. Together, manure and synthetic fertilisers contribute greater CO_2 equivalent greenhouse gas emissions than global aviation and shipping combined. Furthermore, inefficient use results in air and water pollution, resulting in damage to ecosystems and possibly human health.

This study was undertaken to grasp how the UK dairy industry could; reduce or eliminate synthetic fertiliser use, while maintaining profitability, production and stocking rates. Find a pathway for achieving circular nutrients, and understand the role of regenerative agriculture, diverse forage mixes and soil health. This study was directed at Northern Europe where high land prices have led to intensive family farms, with maximised animal density, in a climate similar to the UK, and the USA, home of the term 'regenerative agriculture'.

It's evident from my research and study tour, that there isn't a silver bullet solution, which could resolve dairy farming's reliance on artificial fertiliser. In this report I have focused on industry changes, which I believe will have a positive impact, not only environmentally, but also economically, as nutrient loss is an economic loss. It was non-negotiable that any solutions would be available and beneficial to all dairy farmers, regardless of scale/location etc, meaning any findings would be impactful.

Implementing an efficient nutrient accounting system that uses verifiable data, is fair and logical, has farmer buy-in, offers a range of benefits, and is flexible enough to accommodate unforeseen issues such as TB restrictions, is a tall order. Crucially, it must incentivise genuine behaviour change - not just box ticking or appeasing government requirements. The Dutch system appears to have already achieved this.

On many dairy farms, purchased concentrate feed contributes to an excess of nutrients. While advanced technologies exist to recycle these nutrients, they are often uneconomical to implement. Centralised anaerobic digestion could provide the scale required for all farmers to access nutrient recovery, without the capital expenditure and management responsibilities. Historically, mixed farms maintained a circular nutrient system by balancing resources across multiple co-dependant enterprises. Economic pressures have led to farm specialisation; agriculture must now adopt a nationwide approach to reintegrate this mixed, circular farming model.

The forages grown by dairy farmers play a crucial role in mineralising and utilising nutrients from organic manures, which must provide resilient swards that withstand the increasing extremes of UK weather. However, the current recommended list system lacks data on ryegrass root development, which could be valuable for capturing nutrients and reducing pollution.

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Please note that the content of this report is up to date and believed to be correct as at the date shown on the front cover

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CHAPTER 1: INTRODUCTION

Figure 1: The author, Gary Thompson. Photo: author's own.

I grew up on and now manage a 200-cow autumn/winter calving dairy herd in Co Antrim, Northern Ireland, known as Drumabest Farm. The farm has been in the Thompson family for five generations, and over the last 80 years has moved from a flax milling business, to a mixed pigs, beef and sheep farm to the dairy and renewable energy business I manage today. My knowledge of agriculture has grown through a variety of experiences; I studied at the local agricultural college, including a year's placement on a dairy farm in Scotland, and following graduation I spent several months in Australia working for a harvest contracting business in Victoria, and a dairy farm in Queensland, before visiting farms in New Zealand.

I was an avid member of the Young Farmers' Club and I'm grateful to this organisation for the skills and opportunities it provided, including a three-month exchange programme to Canada.

During my early career I took the opportunity to join a consultant-led benchmarking programme with 10 other farmers, which culminated with an intensive visit to farms in South Africa, a hugely valuable experience in business and herd management.

I'm currently a member of the Agrisearch dairy committee, the Ulster Grassland Society, Dale Farm milk co-op's area council, and my local agricultural show.

I have been brought up to value the role farmers play in managing the countryside, which has fostered a fascination in nature and biological processes. I strongly believe that farms can be profitable, while working with nature in a pragmatic way.

Before my study I had also visited farms in Denmark, Estonia, France and the Netherlands, the latter of which focused on preventing ammonia emissions from dairy farming systems.

CHAPTER 2: BACKGROUND TO MY STUDY TOUR

Global production and consumption of synthetic fertilisers totalled around 195 million tonnes in 2024, with half of all food grown using it. Some claim every other bite can be owed to its use.

As a result, it is widely quoted that globally 2.6 gigatonnes of carbon dioxide equivalent (CO_2e) are produced annually from the production and applications of fertilisers, both manure and synthetic, which is more than shipping and aviation combined.

For farm scale context:

Fertiliser produced.	Tonnes of CO_2e per tonne of product.
Nitrogen	2.6
Phosphate	1.7
Potassium	0.6

Data taken from global carbon accountancy firm Carbon Chain, showing emissions from different types of fertilisers.

Therefore, for a 200-cow dairy farm which applies 50 – 60 tonnes of nitrogen fertiliser annually, equates to a CO_2e of 130 – 156 tonnes. As a result, it's the largest dairy CO_2e contributor from fossil sources.

The data is stark, and contrasts with the National Farmers Union's target for agriculture, of net carbon zero by 2040, and the government's target of net zero by 2050. In addition to CO_2, there are other issues that excess nutrients from chemical fertilisers cause.

2.1 Ammonia pollution

Ammonia is a short-lived pollutant that stays in the atmosphere for only a few hours, depending on weather conditions. However, it can combine with other pollutants, such as nitrous oxide (also released by soils after fertilizer application) or sulphur dioxide (from fossil fuel combustion), to form particulate matter. This persists in the atmosphere for longer, can travel several miles, and potentially poses risks to human health.

Environmentally, deposition of ammonia on sensitive habitats, such as species rich grassland and peatland, has the potential to result in biodiversity loss and a reduction in carbon capture.

In 2022, chemical fertilisers accounted for 13% of the UK's total ammonia emissions, making up a substantial portion of the agricultural sector's contribution, which comprised 87% of the country's overall emissions.

2.2 Water pollution

In excess, both nitrogen and phosphate are water pollutants; the primary pollutant in fresh water being phosphate, and the primary pollutant in marine environments being nitrogen. There are examples of excess nutrients from fertilisers causing water pollution right across the world, including the UK, for example Poole harbour and the river Wye.

In 2023 and 2024, excess nutrients in Lough Neagh, Northern Ireland, led to toxin-producing algae blooms, resulting in poor water quality, wildlife deaths, and the closure of coastal waters for bathing and recreation. This had a significant impact on tourism, and generated negative press for agriculture.

The goal of this study, therefore, was to assess various solutions and provide direction for both the dairy industry and individual farms. The proposed solutions must be practical and applicable to all dairy farmers, regardless of farm size, production system, economic constraints, location, or technical capacity. This broad applicability is required to ensure meaningful and widespread impact.

CHAPTER 3: MY STUDY TOUR

United Kingdom: June 2021

To understand the diversity of the dairy industry, and learn whether all farms were as intensive as Northern Ireland? What were the challenges of different soil types and regions?

Ireland: June 2021

To visit farms with zero chemical N use, achieved with clover and multispecies swards.

USA: June 2022

The home of the term regenerative agriculture. I wanted to visit dairy farmers, broad acre corn and soya producers, as well as market gardeners, who managed soil organically and worked it with their hands.

Netherlands: June 2023/June 2024

To study the challenges and innovations from the Netherlands intensive livestock sector, with strong political will to prevent pollution.

Germany: June 2024

Germany is considered a leader in Biogas production; what systems are available to produce fertiliser from digestate?

Denmark: June 2024

A leader in centralised Biogas, with an intensive livestock sector, and holding the 2024 International Nitrogen workshop.

CHAPTER 4: CIRCULAR NUTRIENTS

I began to consider circular nutrients when a farmer in the Midwest USA said to me: "*The trouble with phosphorus is; it's mined in Florida, shipped to crop farms as fertiliser, it's taken up by plants, embedded in grains, and shipped to livestock farms as feed, and there it stays.*"

This comment helped shape the rest of my study, recalling the law of conservation of mass. Nutrients from fertiliser move through agriculture and the food system, they are not destroyed, the only thing that changes is their location.

As dairy farmers, this circular perspective is often overlooked, with a tendency to focus on isolated components. For instance, we often calculate the nutrients required per hectare for grass silage production, but overlook calculating what is removed from the field in the harvested silage, and how those nutrients are portioned after livestock consume them.

4.1 Dairy cows: How are nutrients proportioned?

Cattle efficiency in converting nutrients like Nitrogen and Phosphorus into growth or milk is approximately 30%, depending on genetics and management practices. Therefore, around 70% of the nutrients from imported grains and fertilisers are either retained in the soil, recycled as home-grown feed, or lost as pollution to the air or water.

4.2 Nutrient management plans

Figure 2: Taken from the roadside in the USA. Note the grass runoff buffer strips in the crop field (centre top) which were common across the States. Photo: author's own.

In Wisconsin USA, farmers tested the soil, and then completed a field-by-field nutrient management plan, water courses and high-risk run-off areas were marked with application restrictions. This is similar to the approach taken in the UK, in particular farms within a Nitrate Vulnerable Zone (NVZ).

Talking to farmers in the US, Europe, and through my own experience, nutrient management legislation is viewed by farmers as a box ticking exercise, lacking direct tangible benefits. This paperwork is often considered unnecessary, frustrating farmers into paying bookkeepers to complete these tasks, so they can get on with the job of farming.

This has led to a complete disconnect between what is on paper, and what happens on the ground; often the person in the tractor doesn't know the nutrient management plan exists. The practicalities of a contractor or farm staff, studying a plan on a field-by-field basis, when under time constraints to get a job done, is unrealistic. As an example, Northern Ireland has been in a NVZ for almost 20 years, and poor water quality still persists. Clearly the current legislation isn't having the desired outcomes.

An organic dairy and arable farmer in Ireland who viewed his farm's nutrients in a circular manner questioned: *"Why is a dairy cow treated as producing 89kg N/year, regardless of system, my cows produce 5,500 l and get 600kg of cake, yet my neighbour's cows produce 12,000l in an indoor system on 5,000kg of cake and his cow is also considered to produce 89kg/N/year. My neighbours' nutrient loading is vastly greater than mine, yet we are both treated the same, where is the driver for efficient use of nutrients?"* I began to search for examples which addressed these issues.

(Note: After my visit, during 2023 Ireland moved to a system of N excretion rates banded by milk output, with optional reductions by reducing concentrate crude protein.)

4.3 Nutrient accounting Case study: The Netherlands

The Netherlands have developed a mass flow nutrient accounting system known as Kringloop Wijzer, where a farm is treated as an island and imports and exports are assigned a nutrient value.

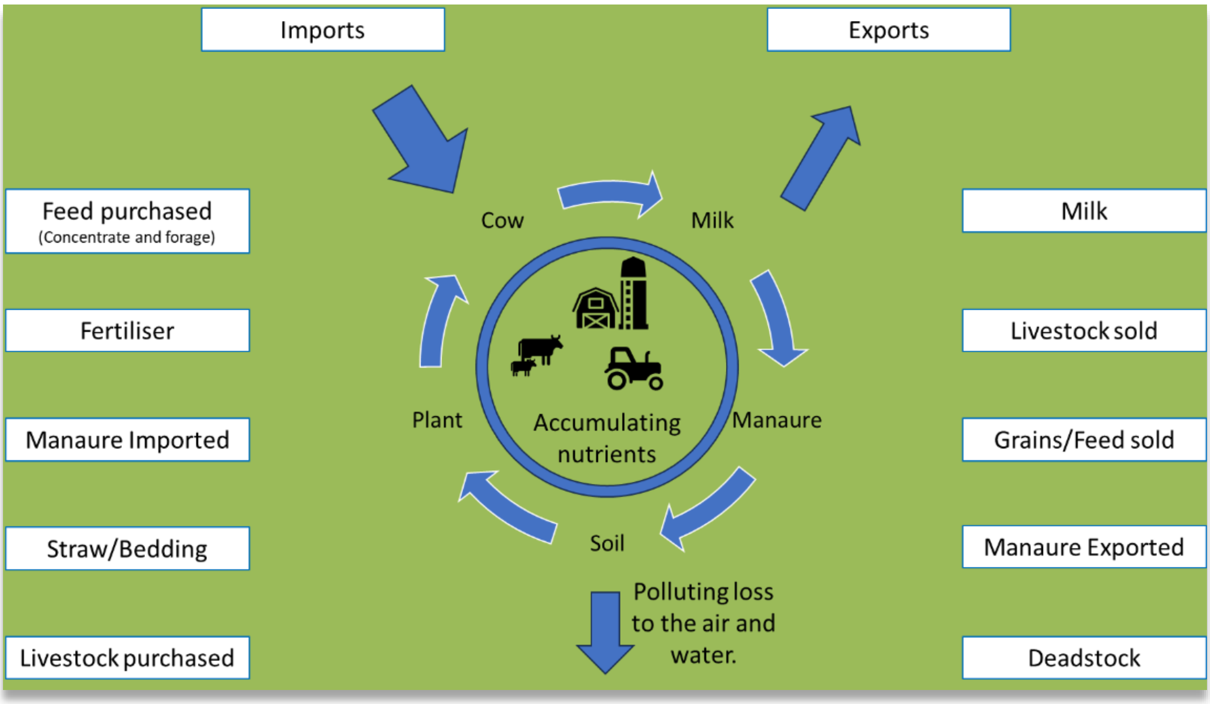


Figure 3. Diagram represents nutrient flows in Kringloop Wijzer. Author's own.

Much of the input data is already pre-populated by; the animal movement system, concentrate and fertiliser suppliers, and milk buyers, who all report directly to Kringloop Wijzer. Farmers are required to record farm to farm movements, for example, FYM and straw.

A total farm nutrient balance for nitrogen and phosphate is generated, with losses modelled according to farm system or actions etc. Milk buyers use the results to reward farmers via environmental bonuses, and government to monitor nutrient excess and risk of nutrient loss to the environment. This system is not perfect and does require some modelling and estimated values, however it captures individual farm management efficiencies.

4.4 Legislation that closed farms: New Zealand.

I undertook several online interviews with industry representatives from New Zealand, to discuss their nutrient management and modelling tool "Overseer," which has been running for over two decades. Overseer is a complex, highly developed modelling tool, accounting for details such a Sulphur deposition from the sea, with reference to prevailing winds and farm distance from the coast.

New Zealand's government used this information to establish legislation, restricting dairy farming in pollution hotspots. This has proven costly for dairy farms within the North Island's Lake Taupo catchment area, which were unable to comply with the strict regulations and were effectively shut down.

This is evidence of the complexity of nutrient management and human behaviour, a global issue that requires a balanced approach, that works for both farmers and the natural environment.

4.5 Chapter conclusions

- Nutrients are circular.
- Cows are only 30% nutrient efficient.
- Field by field nutrient planning, has a disconnect between the plan and the field.
- The standardised N excretion/cow values used in UK NVZs have no reward for nutrient efficiency.
- (This remains the case within bands for Ireland and Wales.)
- The Dutch system treats farms as an island and monitors nutrient flow balance.
- Governments elsewhere have been willing to sacrifice production to prevent pollution.

CHAPTER 5: LOSSES TO THE ENVIRONMENT - AMMONIA EMISSIONS

Ammonia is a gas produced when urease (contained in faeces or soil) reacts with urea (in urine or fertiliser). It is then volatised to the air, which leads to a significant loss of nitrogen from circular nutrients in dairying.

If 200 cows were housed year-round this loss could have a nitrogen equivalent of:

Fertiliser	Equivalent product tonnage
Urea 46% N	5.2
CAN 27% N	8.7

Table: Author's own, calculations used are contained in the appendix.

Field applications with a splash plate during the summer months could cause further losses, equivalent to those in housing.

5.1 Case study: The Netherlands

The Netherlands emits more nitrogen compounds per hectare than any other European state, and has been striving for decades to reduce ammonia emissions. Much of agriculture's understanding of ammonia emissions has come from the research and experience of the Netherlands. Apart from the obvious measures of reducing emissions through low emission slurry spreading techniques, there are several other commercially available technologies.

Figure 4: JOZ Gazoo Netherlands. Photo: JOZ Gazoo.

The JOZ Gazoo and Lely Sphere capture farm ammonia emissions and create a liquid fertiliser, ammonia sulphate, with a 6-9% nitrogen content. GEAs manure enricher works a little differently by cracking the air, creating nitrous oxides that assimilate into, and acidify slurry, creating an enriched manure.

Complete prevention of ammonia loss is not an achievable target for any technology. All of these systems have their own benefits and drawbacks from an ammonia capture/ fertiliser production standpoint. However, the capital cost (£250-£500k) and annual costs of £50k+, alongside health/safety and management requirements, means the only realistic applications are for year-round housed dairy herds greater than 500 cows.

5.2 Case study: Stan Bosman, dairy farmer, Netherlands

I visited the farm of Stan Bosman in the Netherlands who milked 160 cows with three robots. On the day I visited his contractor was shallow injecting slurry on silage aftermath, which was being mixed 50:50 with water from a drainage channel. This dual mitigation approach is commonplace in the Netherlands as a method of reducing field ammonia emissions, by capturing the ammonia with excess water and placing it into the soil.

Figure 5: Slurry injection with the addition of water on the farm of Stan Bosman, the Netherlands. Photos: author's own.

Stan was also trialling a system of his own design to reduce housing ammonia emissions, gasses from below ground slurry storage were pumped underground and forced through a drainage system, rising to the surface through the drain stone, it is expected that grass roots will capture and utilise ammonia emissions.

5.3 Dutch experience

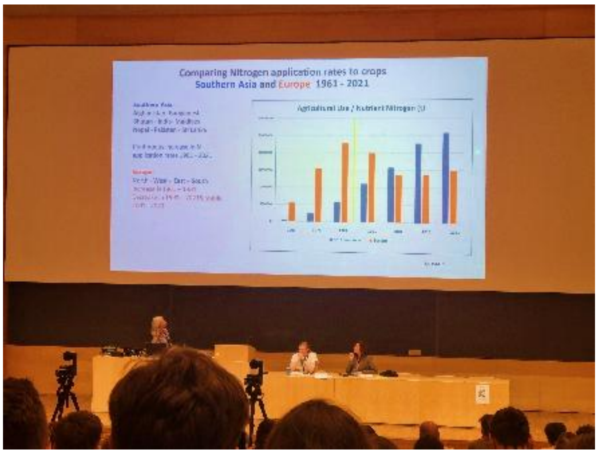


Figure 6: 2024 International nitrogen conference Aarhus Denmark. Photo: author's own.

Following discussions with Dutch researchers at the International Nitrogen Conference in Denmark, management practices, rather than complex technical solutions, remain the best method to prevent country wide ammonia emissions. These management practices include optimising the crude protein level of feed rations, frequent scraping of floors, correct timing of application of fertilisers to coincide with immediate crop need, and the use of inhibitors.

5.4 Chapter conclusions

- Ammonia emissions are a significant nitrogen loss from dairy farming systems, financially and environmentally.
- There is no way to prevent 100% of ammonia emissions.
- Managing cattle and manure correctly is far more efficient and cost-effective compared to relying on complex technical solutions.

CHAPTER 6: ANAEROBIC DIGESTION - THE ECONOMIC SOLUTION TO CIRCULAR NUTRIENTS

The challenge of reducing ammonia loss and exporting excess phosphate and potassium economically could be partially answered by using Anaerobic Digestion (AD). I visited on-farm plants (Germany) and a centralised plant (Denmark), each of which has their own benefits and challenges.

6.1 Case study: Harms pig and arable farm with an AD plant, Germany

Figure 7: Author centre with German scholar Meinke Ostermann left and Jenz Harms right. Photo: author's own.

Located near Bremen in northern Germany, the Harms family has installed an AD plant fed with 10,600 m^3 of pig slurry, with post digestion nutrient recovery and clean water separation.

Ammonia capture to produce fertiliser was a costly and barely viable process as previously explored. The Harms however, used waste heat from the generator engine for vacuum evaporation, evaporated water was returned to the environment, achieving a reduction in volume of almost 40% and economic viability.

Input	**Weight, tonnes**
Pig slurry	10,600
Output	
Seperated solids	1500
Clean water	4500
Concentrated slurry	4500
Ammonia Sulphate	100

Table: Input and output from the Harms AD and nutrient recovery plant.

Ammonia sulphate liquid fertiliser was produced at 9-10% nitrogen, separated solids were high in phosphate and potassium, enabling specific nutrients to be aligned with specific crops and crop need at various growth stages, maximising growth and reducing losses.

6.2 Centralised anaerobic digestion

In exploring a centralised system, I visited Sustainable Bio Solutions AD plant near Kliplev, Denmark producing bio-methane for direct injection to the gas grid, by processing approximately 850,000 tonnes of raw waste streams, of which 60% was animal manures. To supply this an average of 90 trucks in and 90 trucks out were required every day of the year.

The continuous truck movements highlighted the challenge of a centralised system, in particular the movement of low dry matter, low energy density slurry. The plant had no surplus heat available for vacuum evaporation, (due to direct to grid gas injection) therefore the spent digested product had the same problem of high-volume low-density nutrients that due to the wet autumn and spring of 23-24, crop growers, with poor trafficability soil conditions, didn't want to apply.

Figure 8: Sustainable bio solutions anaerobic digestion plant Klipev Denmark. (For reference of scale, note the blue shipping container, and tractor, centre top of this photo.) Photo: author's own.

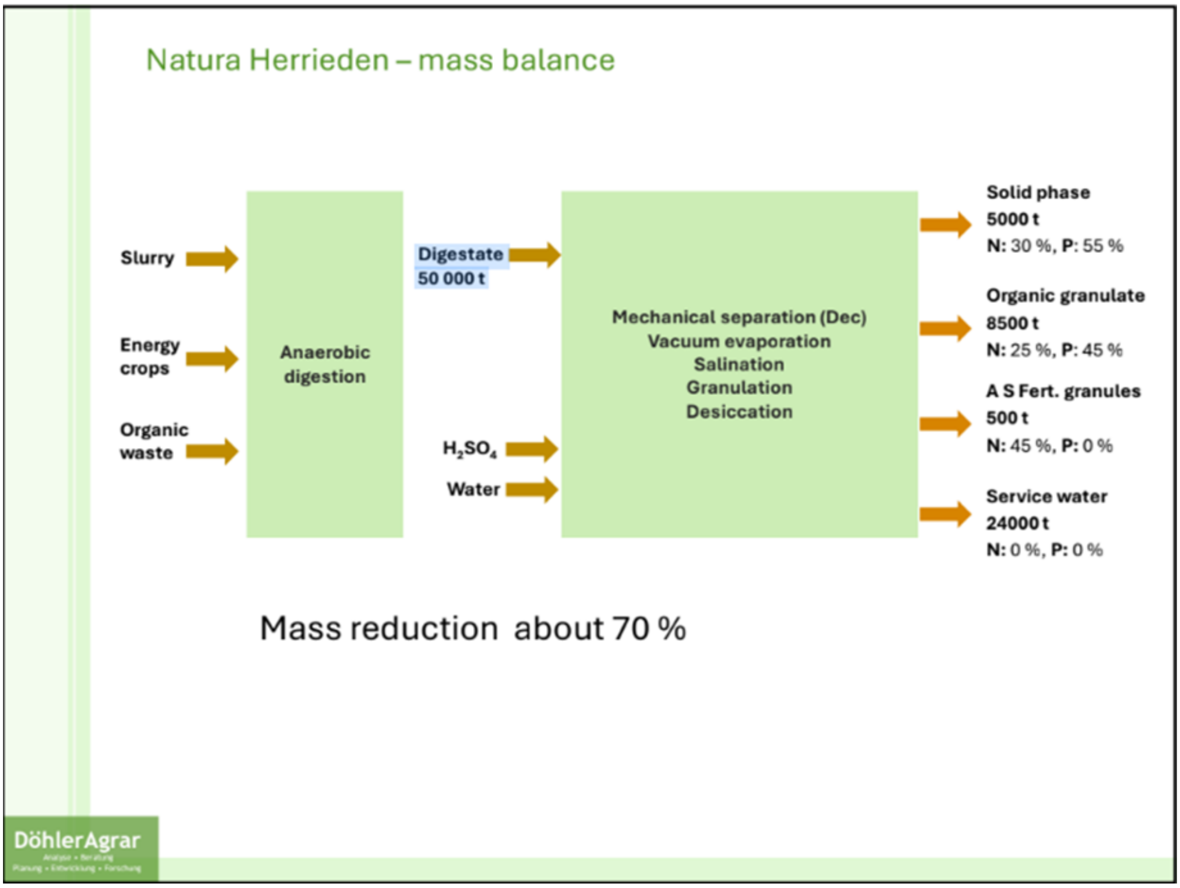
Transport to AD, The solution:

A 2023 DAERA- funded small business research initiative (SBRI) at BH Estates in Northern Ireland, demonstrated that separating bovine slurries and transporting the solids, (25-30% dry matter) to a local anaerobic digester, contained 75-80% of the energy value of grass silage.

Therefore, if grass silage was valued at £40/t, delivered slurry solids have a theoretical value of approximately £32/t, (before taking into account local practical and regulatory challenges,) making separation and bulk transport of slurry solids by truck a viable possibility.

Transport from AD; The solution:

Below is a mass flow chart for Natura Herrieden anaerobic digester in Germany. Ammonium sulphate granulated fertiliser is produced at 45% Nitrogen, with zero Phosphate making it comparable with urea and compatible for use on livestock farms. Other organic based manures produced are suitable for arable farms. Although I have yet to visit, this is the most modern post digestate, nutrient recovery plant I have found.



6.3 Chapter conclusions

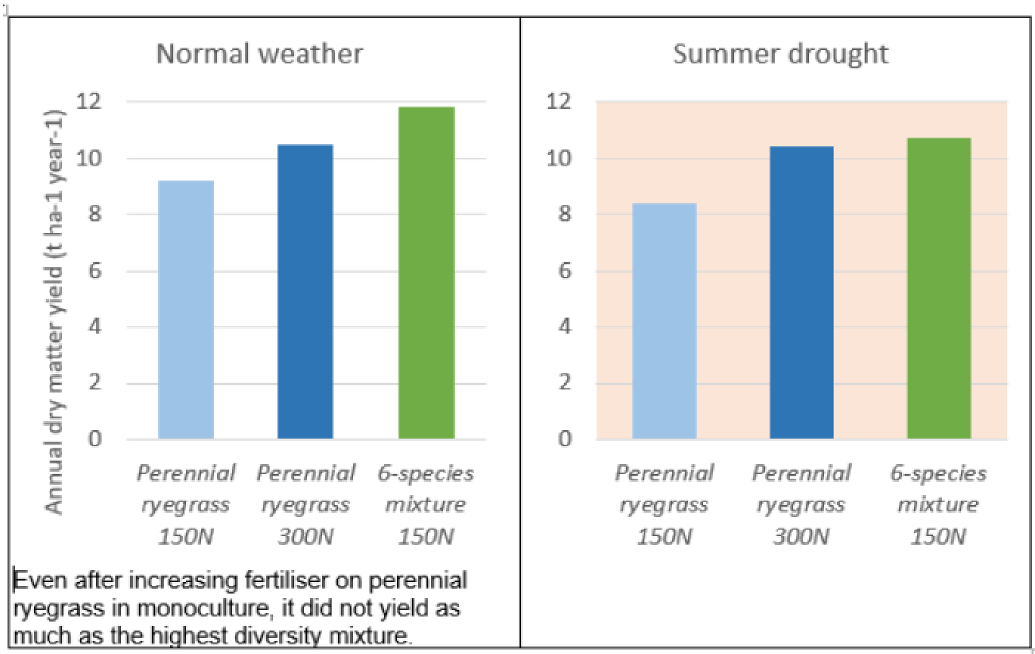
- On farm anaerobic digestion and nutrient recovery may be viable for larger dairy farms, by recovering clean water and segregating nutrients for optimal use.
- Exporting separated slurry solids to anaerobic digester plants, leverages their scale for economically viable nutrient recovery and transport to grain producers, achieving circularity.
- Centralised large-scale AD makes nutrient recovery economically viable on all scales of dairy farms, therefore is likely to have the greatest impact.
- Significant road haulage is required, even when separated manure solids are used.

Chapter 7: Grass breeding

My curiosity for grassland genetics came from my observations of regenerative agriculture and basic learnings of soil biochemistry, which developed my understanding of the critical role that deep and diverse root systems play in maintaining soil health and nutrient acquisition, in particular phosphorus.

When conversing with grassland farmers from across the UK and Ireland, their frustration with extreme weather is evident; poaching during persistent rain or wilting during drought. This reinforced the importance of robust root development, which are qualities possessed by multispecies swards.

I visited a number of farms and research facilities in the UK and Ireland growing multispecies swards, who monitored sward dry matter production, animal performance and soil health. Most have shown increased sward and animal production which was positively correlated with soil and animal health.



Research from Teagasc, Johnstown Castle and Trinity College Dublin shows that multi-species mixtures receiving 150 kg per hectare per year of nitrogen fertiliser, out-yielded perennial ryegrass monocultures receiving double that amount of fertiliser (300 kg per hectare per year).

The results such as those in the table above, were common in researched multispecies swards, where the nitrogen produced by red and white clover coupled with diverse deep rooting plants, such as chicory, enable superior productivity with a reduced rate of applied nitrogen.

The main challenge with multispecies swards is a lack of persistence. A periodic decline in species has been observed, the experiences of others align with my own, following these trends:

- Red clover largely disappears after year one.
- Chicory largely disappears after year two.
- Plantain disappears after year three.
- Timothy reduces after year four.
- At year five-six all that remains is ryegrass and white clover.

Unfortunately, this data is not captured during research, as trials are often conducted over one to three years, with a ryegrass or ryegrass and white clover sward used as a control. Given that it's common for ryegrass swards to be reseeded on farms every ~ 10 years, any trials on productivity should be carried out over this time scale.

If the benefits of multispecies swards are to be fully realised, then reseeding would need to take place every four to five years. Given the loss of productivity and additional costs during the reseeding process, the benefits of multispecies swards over ryegrass during a 10-year period may be negligible. At the time of publishing, I'm not aware of any research which has quantified this.

Multispecies swards offer several benefits; however, their management can be challenging, and their lack of persistence means they are not a perfect solution for reducing fertiliser use. In addition to nitrogen fixation, their positive effects on sward productivity stem from increased root diversity and depth, resilience to extreme weather, improved soil health, and enhanced nutrient and mineral acquisition. Given these advantages in rooting characteristics, why hasn't the development of ryegrass-only swards focused on capturing these benefits?

7.1 Grassland Genetics.

When grass varieties are being assessed, all key nutrients are chemically over supplied and plots are randomised to ensure the only limiting factor are the genetics themselves. On the face of it, this makes sense. The variety with the highest yield logically has the highest nutrient use efficiency. This has resulted in a yield increase across varieties in the recommended lists of around 0.5% per year or 10% in 20 years. The focus of the recommended list criteria has been yield, digestibility, and disease resistance.

In discussion with the grass breeding industry, it's clear that root development could be increased, however, it would likely come with a forage yield penalty as the leaves would have to support a larger root mass. For this reason, these genetics would never see the marketplace as they wouldn't meet the production threshold of the recommended list.

In addition, grass breeding plots are often conducted on the same sites for multiple years, sometimes decades with no animal manures or crop residue returned to the ground, leaving low organic matters and unhealthy soil. As a result, grasses have no option other than to be reliant on a linear chemical nutrient supply, fed from the surface, as few nutrients are available via mineralisation, potentially furthering selection for chemically reliant varieties.

(Note: Grass plots are rotated with other trial crops however the process is similar with total crop removal and no organic manure applied.)

7.2 Chapter conclusions

- Farmers are experiencing variable climate challenges resulting in erratic yields and challenging management.
- Multispecies swards have a superior short-term yield even with medium fertiliser applications, their downfall is persistency.
- The forage breeding industry has achieved high yields of high-quality forage from a high chemical fertiliser input.
- To some extent root mass has decreased which has an inverse relationship with increased forage yield.
- Test plots can have poor soil quality, with constant organic matter removal, no animal manures applied and chemical nutrition only.

Figure 9: Farm manager Kevin O'Hanlon explaining grazing of multispecies swards on Pollards Organic farm Co. Wexford Ireland. Photo: author's own.

CHAPTER 8: DISCUSSION

This study has been challenging, vast in its scope with complex problems and opposing views. I have tried to find the balanced middle ground. There are many new technologies or practices I considered such as regenerative agriculture, or slurry additives (some of these are highlighted in the appendix of this report,) which could have significant applications for individual businesses; however, they do not yet have universal success.

Reducing chemical fertiliser use in dairy farming will be a slow process; going too fast without the correct knowledge and tools will lead to a loss in production and negative land use change at home or overseas. I have tried to focus on fundamental industry-wide changes, which, when adopted, would have the biggest impact.

8.1 Using nutrient accounting to drive behaviour change

Economic pressures driving high stocking rates and milk yields have resulted in excess nutrient being imported onto many UK dairy farms in the form of concentrate feed. Before farmers can manage this excess, which in effect is pollution, it must be measured. Only then will circular nutrients be widely understood. Recognition by farmers of the loss of circular nutrients within their business and a clear return on capital investment are likely to drive behaviour change much more effectively than legislation.

The first step is to develop a clear and logical understanding of the issue. The Dutch appear to have established an effective system, particularly through the pre-population of nutrient movements by milk buyers, feed companies, and other stakeholders. This approach not only reduces the administrative burden on farms but also enhances accuracy and minimises the potential for creative accounting.

The current standard unit system (used in UK NVZs) fails to drive meaningful change. By allocating 100 kg of nitrogen per cow (Northern Ireland example) annually, divided by the farmed area, removes any real incentive for farmers to improve nutrient efficiency.

(The banded system introduced in Ireland and Wales in 2023 is a step forward, however, it still contains no efficiency incentives within production systems.)

In contrast by calculating a farms import and export balance, highlights management practices, which reduce excess nutrient losses or nutrients inefficiently retained on farm.

Examples are:

- Driving milk from forage.
- Feeding a reduced protein or phosphate diet.

- Understanding a farm's phosphate balance - negating the need for chemical P fertiliser.
- Using efficient animal genetics.
- Optimum application timing of manures and fertilisers.
- Nitrogen produced by legumes and the soil.

Efficiencies from cumulative actions are captured and rewarded by maximising milk production per Ha under a limit, (currently 170Kg/N/Ha/year in UK NVZs) by nutrient accounting.

I understand the challenge, cost, commitment and risk such a system would entail, given the experience of some in New Zealand. However, to do nothing will result in increasingly restrictive legislation. Negative press around nutrient loss or carbon footprint tars all farmers, but only when individual businesses become responsible, will the industry's nutrient efficiency improve.

8.2 Nutrient KPI benefits

Nutrient accounting effectively produces nutrient KPIs, although the data is aggregated, it still highlights outstanding farms and the combination of measures which are the most nutrient efficient for a given production system or location, which gives opportunity for peer-to-peer learning.

Losses to the environment can be aligned to a purchased fertiliser price, therefore a return on investment can be calculated for loss preventing equipment or techniques. State funding could be directed to the most impactful actions and those farmers who need assistance.

8.3 Antibiotic reduction: an example of progress.

The reduction in antibiotic use achieved by the farming industry over the last number of years, is a positive example of a collaborative approach to a complex problem, with an emotive public perception.

8.4 Anaerobic digestion

The economic drivers to spread production costs, over as many litres of milk/cow as possible, achieved by imported concentrates, is unlikely to change. Using nutrient accounting to identify excess nutrients contained in those concentrates is the first step. The next challenge is to export those excess nutrients back to arable farms, in an economically viable way.

Figure 10: Mobile slurry separation, BH Estates, Northern Ireland. Photo: Ivor Lowry.

Removing slurry from dairy housing as quickly as possible, before separating slurry solids and exporting them to centralised anaerobic digestion plants, where organic matter is mineralised, allowing clean water to be recovered, creating recycled chemical and enhanced organic fertilisers, will achieve circular nutrients from an energy positive process. This nutrient recovery strategy seems poised for adoption across Europe. However, since these processes require significant capital investment, incentives from central governments will be essential to bring them to fruition.

8.5 Could ryegrass be bred to prevent nutrient loss in dairy farming systems?

At the conclusion of my study, highlighting a change in the focus of grass breeding towards resilience in challenging weather, and efficient nutrient acquisition from organic manures, is the idea I feel most strongly about. I don't think the dairy or grass breeding industry has fully assessed its potential in reducing chemical fertiliser use.

8.6 Farmer behaviour: the hidden excess chemical fertiliser use

Farmer response to a forage deficit is twofold. Firstly, extra fertiliser is applied in a desperate effort to stimulate growth, exacerbating the problems of excess nutrients. Secondly, to mitigate any forage deficit, extra concentrate feed is purchased along with the embedded nutrients contained in them.

When discussing grassland challenges with farmers from right across Europe, the increasingly unpredictable seasons with extreme weather challenges are a burning topic, robust deep roots are without doubt one of the mitigation solutions. On top of this, negative press around water quality, with the finger pointed at agriculture is a frustration, yet there is simply no data available where farmers can select forages or crops with robust, aggressive root systems.

The post-World War II breeding strategy, aimed at maximising production, relied on the logic of oversupplying nutrients in grassland trial assessments, where superior yield was equated with high nutrient use efficiency. This doesn't align with the environmental constraints placed on today's farmers. On most dairy farms phosphate and much of the nitrogen is supplied via imported cattle feed, and subsequently animal manures, which must be mineralised or obtained from previously applied soil reserves. This requires plants to communicate with, and supply energy to, the soil biome in return for nutrients.

I'm cautious not to make spurious claims, however I can see a host of potential benefits, of enhancing the below-ground capability of grass varieties, and extending the persistency of multispecies swards which include:

- Increasing nitrogen fixation by free living bacteria such as Azotobacter.
- Extending the grazing season, preventing housed ammonia emissions.
- Increasing the nitrogen capturing envelope from urine patches or applied nitrogen.
- Reducing excess nitrogen at depth, possibly reducing anaerobic nitrous oxide emissions.
- A balanced forage mineral profile.
- Alleviating shallow compaction, preventing run off.

Grassland genetics and the recommended list system have contributed hugely to the productivity of livestock farms over the last 60 years; however, the current strategy no longer fully aligns with all of the requirements of livestock farmers. I feel that the forage breeding industry and the recommended list system have the potential to play a central role in capturing circular nutrients and fixing atmospherical nitrogen.

CHAPTER 9: CONCLUSIONS

Farmers need to view nutrients as part of a circular system. When framed this way, it can drive significant behaviour change, promoting practices that conserve and recycle nutrients effectively. For this shift to be successful, automatic data capture, generating clear KPIs must be established, equating to nutrient accounting that rewards efficiency.

By moving slurry solids economically for energy, mineralised nutrients can be captured viably post-digestion. With numerous AD plants required and a high capital cost involved, roll-out will likely only be possible with government incentives attracting city investment.

Ryegrass genetics and the recommended list system have significant potential to improve resilience, mineralisation, nutrient capture and soil nitrogen production. Multispecies and clover swards are useful tools but lack persistency.

CHAPTER 10: RECOMMENDATIONS

Farmers

Within the farm gate, focus on optimising farm productivity, economic and nutrient efficiency are the same thing.

Behaviour change, such as spreading manures at the appropriate times by understanding their value, as a fertiliser not a waste.

Experiment with what works on your farm. All farms reducing some fertiliser and recycling nutrients, will be more impactful than a few becoming organic.

Industry

Design and fund a nutrient accounting system that works for all stakeholders, that's flexible under circumstances such as TB restrictions. Nutrient accounting is about long-term behaviour change, not legislative box ticking, operated by government.

Lobby government for incentives and relaxed planning towards anaerobic digestion plants with nutrient recovery.

Reevaluate the breeding strategy for forages in the face of a changing climate and increased environmental constraints.

(During spring 2025 Defra is holding a plant breeding strategy review for implementation in 2026.)

CHAPTER 11: AFTER MY STUDY

I appreciate now more than ever that British dairying has a positive story to tell, although there are huge challenges ahead as regards nutrient management. However, with change comes opportunity, by creating circular nutrients we can reduce costs and pollution, create jobs and retain money within our economy that used to go overseas to purchase fertilisers.

I took part in a research initiative to cost viable transport distances for slurry solids to AD. 140t of solids were sent to produce renewable energy.

I travelled to Birmingham for a Defra-led plant breeding strategy workshop to highlight some of the farm challenges the current system of plant breeding wasn't addressing.

There are potential biological solutions to reducing chemical nitrogen which are beginning to gain a foothold in the arable sector, such as applying nitrogen fixing bacteria to growing crops, I would like to explore its potential use in the grassland sector.

ACKNOWLEDGEMENTS AND THANKS.

I would like to thank those who took time out of their day to meet me, talk and explain, send lengthy emails, feed me, put me up or make me a brew. It was a privilege to meet all of you; thanks for your frank and candid responses to all of my questions.

I would like to thank the team at Drumabest Farm for running the farm and meeting the challenges in my absence. My partner Helen, who has supported me, and family who've proofread or helped with my dire computer literacy.

I would also like to thank the Nuffield Farming Scholarships Trust for giving me this opportunity and the Thomas Henry Foundation for kindly sponsoring my scholarship.

APPENDIX 1. REGENERATIVE AGRICULTURE

At the start of my study the term 'regenerative agriculture' was new to the UK, its advocates based in the USA claimed it had solutions for many of the challenges faced by modern agriculture, including reducing the use of chemical fertiliser. Its origin stems from the desire to increase nutrient cycling by improving organic matter, soil biology and living roots, to retain moisture and therefore resilience to drought in semi-arid regions.

Below is a diagram that illustrates these principles. When considering them as a grassland dairy farmer, four key principles of regenerative agriculture are already met. However, the primary challenge lies in the lack of crop diversity, as monoculture ryegrass dominates the pasture, limiting the potential for a more diverse and resilient ecosystem.

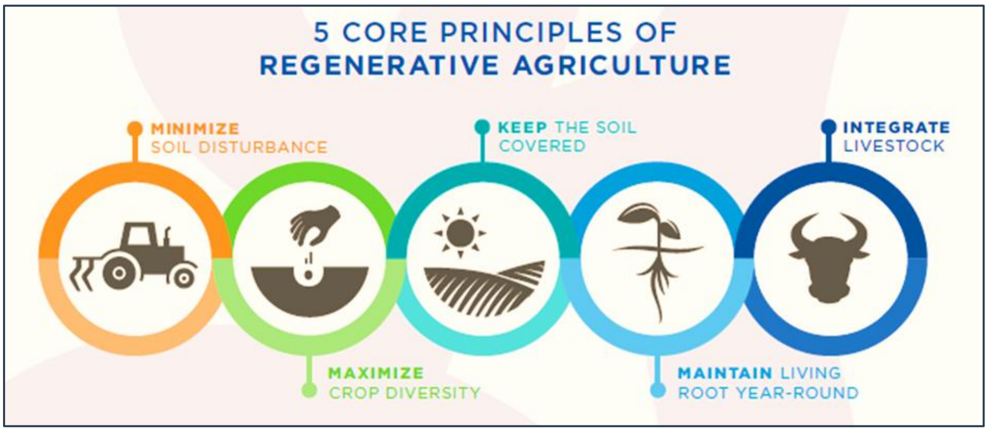


Figure 11: Graphic from https://www.landscapedna.org/actions/prevention/regenerative-farming/

I visited the Rodale Institute in Pennsylvania USA, regarded as the birthplace of regenerative agriculture. The institute focuses on how soil health is enhanced through plant diversity, deep root systems, the use of animal manures, and the practice of no-tillage farming.

It's common in the USA for soils in corn/soybean rotations to resemble sand in colour, lacking organic matter and carbon, which are critical for soil health. (Soil colour can be a basic indicator of organic matter, much like the difference between a sandy beach and a peat bog.) These farms rely heavily on chemical fertilisers, as no nutrients are available for mineralisation.

In contrast the soils on livestock farms I visited in the UK are some of the darkest and richest in carbon and organic matter that I've seen anywhere. The current condition of soil health on UK livestock farms, is the target of regenerative crop farms in the USA.

Understanding the limiting factors of productivity

When I visited dairy farms practicing regenerative agriculture in New England, I observed only minor differences between their methods and those we would recognise as organic farms in the UK.

However, in the hotter drier Midwest many of the regenerative dairy farms I visited practiced tall grass grazing, a method where cows are turned out onto native grasslands with vegetation ranging from 0.5 to 1 metre in height. Cows are allowed to selectively graze the herbs, clovers, and grasses they prefer, consuming about a third, trampling a third, and leaving the rest standing. As a grassland farmer from Northern Ireland, this approach made me cringe due to the apparent wastefulness, as it contrasts with the total defoliation grazing practices I'm accustomed to.

Figure 12: Tall grass grazing in Wisconsin Mid-west USA. Photo: author's own.

To the contrary, farmers were boosting productivity by adapting to the specific limiting factors of their farms. In the Midwest USA, the main constraints on soil and plant productivity include:

- Hot, sometimes dry summers, punctuated by thundery downpours.

- Extreme sub-zero winters, which kill ryegrass; only deep-rooted native plants survive.

Grazing down to complete defoliation would expose the soil to intense heat and sunlight, causing moisture to evaporate, halting plant growth until rain arrives, (which might not come for the rest of the season.) This leads to the soil baking hard, killing soil biology, preventing manure deposits and other organic matter from being incorporated, and when rain does eventually come, it runs off the bare soil quickly, taking valuable soil particles and nutrients with it.

By practicing tall grass grazing, the inverse occurs, the trampled third of the grass forms a dense mat on the soil surface, creating a layer that traps condensation, keeping the soil damp and cool. This helps maintain healthy soil biology and provides a habitat for invertebrates to break down animal manure and other organic matter. The standing third of the grass continues to photosynthesize, feeding the soil biology through deep root systems, which help maintain an open and friable soil structure. As a result, during heavy rainfall, the soil is protected and porous enough to absorb water, preventing runoff and enhancing moisture retention.

Applied slurry was able to meet the nutritional needs of the sward early in the grazing season. Clover was one of the first plants to recover through the trampled thatch after grazing, which supplied the necessary nitrogen for the remainder of the season. However, this system was only effective because the grazing rotation was 40 to 60 days long, which led to much lower dry matter production and stocking rates. As a result, nutrients were not the limiting factor.

Limiting factors

Once synthetic fertiliser inputs are removed from a farming system, it becomes reliant on the farm's natural resources, making it crucial to understand and address natural limiting factors.

What are the UK's grass growth and utilisation limiting factors?

It's somewhat of an impossible question to give a definitive answer as it depends on a farm's location, soil type and weather from one year to the next, however it is an important question and one which is at the core of this topic which I repeatedly found myself asking during the course of this scholarship.

For some grazing farmers in the UK who annually find the pasture withers during summer droughts, then some form of tall grass grazing using deeper rooted grass species may be of benefit, however for many livestock farms in the wetter west, lack of moisture is rarely a problem and nitrogen often is the limiting factor, or too much rain and saturated soils limit productivity by preventing efficient utilisation and poaching.

Enterprise stacking

One of my most insightful visits was to the 1,100-hectare regenerative farm owned by Monte and Robyn Botten's near Cambridge, Illinois.

The regenerative techniques they employed included growing cover crops as green fertiliser, using roller crimping methods to terminate the cover crops, followed by direct drilling. Additional practices involved reducing crop protection chemicals and integrating cattle into their large-scale farming operation.

Figure 13: Grain storage Monte Botten's USA. Photo: author's own.

Despite running a large-scale farm, Monty's passion was Grateful Graze, a direct-to-consumer business offering grass-fed pork, chicken, eggs, and beef. In this integrated system, the waste from one enterprise supported the next. The cattle were managed using a leader-follower approach: fattening cattle grazed first, followed by cows and calves, and a week later, laying chickens were introduced. The chickens scattered the cattle manure and consumed the fly larvae within it, reducing the fly population while spreading both cattle and chicken manure across the pasture as natural fertiliser. Combined with the use of cover crops, this approach eliminated the need for chemical fertilisers and fly treatments, boosting soil health, increasing organic matter, and benefiting the arable operation whose grains supplemented the livestock.

I'd seen this sort of enterprise stacking a number of times in the USA, creating circular nutrients, similar to traditional mixed farms in the UK.

Conclusion

Regenerative dairy, similar to organic farming, involves a reduction in stocking rate, leading to decreased productivity per hectare. This decrease results in higher costs and lower returns, particularly given the limited land availability and higher land prices in the UK and Europe. Without financial support or premium milk prices, the economics often don't stack up.

I found few directly transferable regenerative agriculture practices; however, the five principles of regenerative agriculture are fundamental to soil health. Enterprise stacking and understanding a farm and businesses limiting factors make sound environmental and economic sense.

APPENDIX 2: FOLIAR APPLIED LIQUID FERTILISER

Foliar applications of nutrients are common in the arable sector, they can work in grassland with a disciplined approach, but it's not for everyone and there is a considerable amount of extra work involved. Here are some of the advantages and drawbacks of the technique.

Advantages:

- Reduction in nitrogen use as the plant efficiently takes up nitrogen.
- Reduction in nitrous oxide and ammonia emissions as the applied nitrogen never contacts the soil.

Disadvantages:

- Ineffective immediately after cutting/grazing – requires a green leaf canopy to be absorbed.
- Risk of causing nitrogen toxicity in cattle, application must be completed at least five days before grazing.
- Cannot be applied during hot dry weather; application will scorch the pasture.
- Cannot be applied during rain as it will wash off before absorption.
- Application is considerably slower as it must be sprayed rather than broadcast.
- Will not deliver enough nitrogen in one application for a cut of silage, requires multiple passes.

Some farmers may find this works for them, however I felt it's an unsuitable solution for all, as it requires eight days post-grazing to build leaf and five days before grazing to prevent nitrogen toxicity in cattle, which leaves a very short window for suitable weather!

APPENDIX 3: BIO-STIMULANTS

Bio-stimulants are a really interesting topic, when discussing bio-stimulants during a visit to Novo crop in the Netherlands who carry out research and nutrition for commercial greenhouses.

My guide stated: *"Water is the greatest bio-stimulant on earth."*

Which perfectly explains bio-stimulants. During a year of drought, water is a very productive bio-stimulant and will significantly increase yields, yet during prolonged wet periods additional water would have no increase in yield, and in the case of saturated soils would have a negative effect on yield.

By applying the principles of the water example above, bio-stimulants will only achieve consistent results when scientists fully understand the limiting factors of a biological process. By applying the correct additive to remove that limit, consistent results could be achieved.

Many of the biological solutions I studied have sparked opposing viewpoints. Some farmers firmly believe in their effectiveness, considering them essential farming tools, while conventional science struggles to find consistent results.

Biological slurry additives are an excellent example, many farms I visited were happy with the outcomes when using slurry additives, often there was little or no crust formation and the slurry was easily mixed. Individual farm trials had shown increased grass growth when using this treated slurry.

However, research stations had mixed results, and often couldn't find consistency in their trials, which was the case when I visited Teagasc's Johnstown castle in Co Wexford during 2021. It's difficult to know whether slurry additives prevent gaseous loss during storage, or mineralise nutrients contained in organic matter which without treatment would have remained locked up and have been mineralised and utilised after field application. To add to the difficulty in drawing conclusions with biological slurry additives there are commercial sensitivities which prevent full access to research. For these reasons I have been unable to draw conclusions and have not included it in the main body of my report.

Conclusion

Bio stimulants have huge potential however, until we understand the full microbiome and biochemistry of slurries, soil, and their relationship with plants, as opposed to outcomes-based research, farmers are unlikely to be able to fully utilise any potential.

APPENDIX 4: NITROGEN FIXATION - CLOVERS

White Clover

White clover has the ability to fix around 150kg of atmospheric nitrogen per Ha, to achieve this swards should contain 30% clover, although, as white clover spreads via stolons during the grazing season, it will have the visual appearance of 50-60% of the sward during August; any less than this and expected nitrogen production will not be met.

What must be noted is that the nitrogen fixed by clover is not available to other plants in any great quantity until the clover plant either dies, or is defoliated by cutting or grazing, causing root dieback. Nitrogen is released as the roots decompose, providing fertiliser for the following crop, not the current one.

For this reason, to maintain sward productivity early in the season additional nitrogen will be needed either from chemical fertiliser or manures.

I visited a farmer in the UK who had made huge strides in reducing chemical nitrogen using ryegrass, cocksfoot and white clover swards. It was clear white clover had dominated the sward in late summer, as when I visited in late October the clover had died back for the winter, leaving patches of bare soil which I estimated across the field at 5-20 %. I realised at this visit that balance must be maintained, the right plant should be in the right place; there is no point reducing the use of chemical nitrogen only to lose soil and nutrients via runoff due to heavy rainfall overwinter.

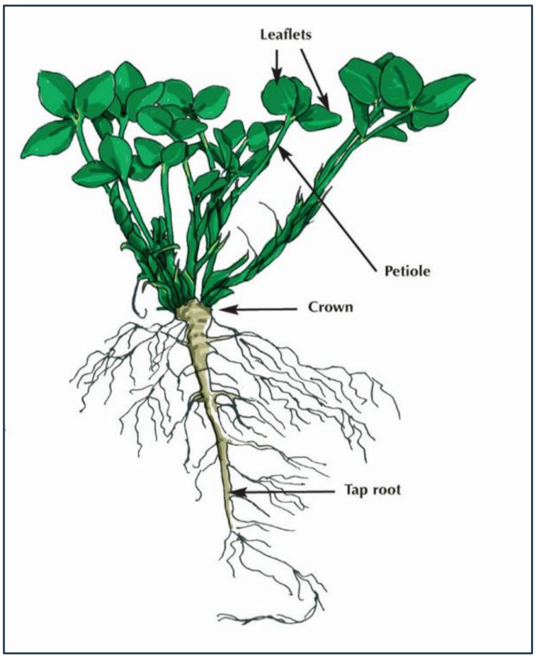


Figure 14: Red clover. Infographic: AHDB

Red Clover

Red clover has significant potential to capture nitrogen, approximately double that of white clover, at up to 250kg/ha/year. It is typically used in silage swards because the plant will die if the crown is damaged by overgrazing or cattle trampling (see diagram). I have observed on multiple occasions red clover/ ryegrass silage swards where the headlands and wheeling's of silage or slurry equipment have killed the red clover due to compaction or crown damage.

Further challenges are establishment, weeds, bloat, and silage preservation. Information can be found at:

AHDB https://ahdb.org.uk/knowledge-library/establishing-clover

Teagasc https://www.teagasc.ie/crops/grassland/grass10/clover/

APPENDIX 5: THE TROUBLE WITH PHOSPHORUS

Within a matter of days, applied phosphate fertiliser binds to soil or organic matters, and as a result becomes unavailable to plants. The standard phosphorus test used in the UK is Olsen P, which is designed to be the UKs best predictor of plant available phosphorus. This however is not necessarily a true reflection of the elemental phosphorus contained within soils. Below is a diagram which demonstrates why phosphate availability is influenced by the correct pH, and that fixation can occur to aluminium and calcium.

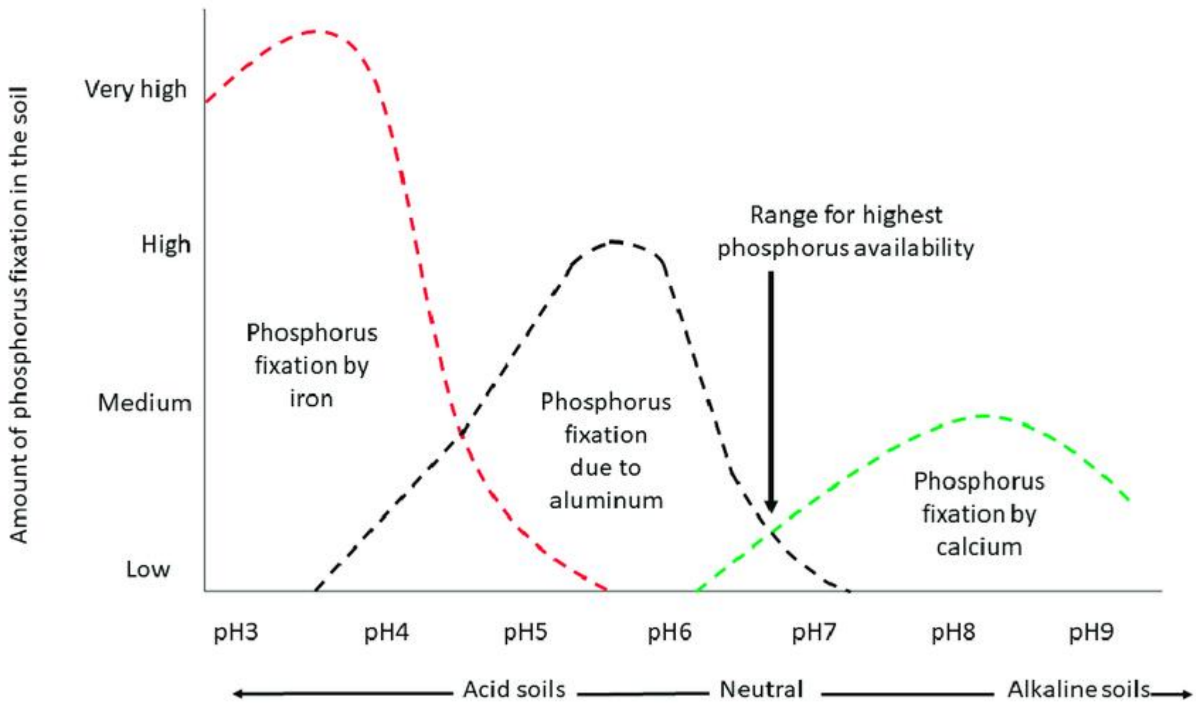


Diagram: General qualitative representation of soil phosphorus availability as impacted by PH. Graphic: Redrawn from Price.

https://www.researchgate.net/publication/333695040_A_Critical_Review_on_Soil_Chemical_Processes_that_Control_How_Soil_pH_Affects_Phosphorus_Availability_to_Plants

Reference for the lockup of phosphorus in basalt soils: Ref A.A.W. Bell', J.S. Bailey2>", R.V. Smith2 & M.M. Allen3.

As an example, below / overleaf is a result of a soil sample from my farm, even though the sample has an elemental reserve of over three tonnes per hectare, plant available phosphate estimated via the Olsen method is less than 40% of what is required, leaving a soil index of 1.

Major Elements in Elemental form		Reported as kilograms/hectare - elemental (kg/ha) CROP AVAILABLE NUTRIENTS			TOTAL IN SOIL Reserves
		kg/ha DESIRED	kg/ha Found	Difference	ELEMENTAL kg/ha
Calcium	Ca ++	6785	6250	-535	24793
Magnesium	M ++	582	714	132	43317
Potassium	K +	566	663	97	3169
Sodium	Na +	99	116	17	2005
Other elements		7%	3.70		Minor Importance
Hydrogen		8%			
Sulphate	(S03)	137	153.34	17	4395
Phosphate (P205)		196	76	-120	3319

Standard UK index to ISO/IEC 17025-2005

Index Figures

mg/l	Index		Buffer pH	6.8
9.7	1	Phosphorus		
164	2-	Potassium		
178	4	Magnesium		
		Calcium		
		Organic Matter		

UK phosphate is via the Olsen method

Figure 15: Plants deficient in phosphorus will change in colour to a dark green and then to purple. Photo: ABo (pixabay.com) used under CC0.

Farmers across the UK may have noticed purple leaves, as I have on grass and crops during the cool spring of 2023, and especially in 2024, (see left). This discoloration is a typical sign of phosphorus deficiency in crops.

Why is this happening, even in soils with high phosphorus reserves?

As demonstrated in my soil sample, the issue often stems from limited phosphorus availability rather than a lack of phosphorus in the soil itself. Phosphorus from fertilisers or animal manures can be “locked” in a matter of days to forms that plants can't easily access.

Cooler, wetter spring conditions can also slow down microbial activity and root growth, further limiting phosphorus uptake and resulting in visible deficiency symptoms, like purple leaves, despite high phosphorus levels in the soil.

The table below demonstrates the relationship phosphate has with PH and temperature.

pH & P Availability

Soil Ph	Relative Availability of Phosphate	Effect of soil temperature on relative availability of soil phosphate			
	%	13ºC	16ºC	18ºC	21ºC
5	23	7	10	17	23
6	46	14	20	34	46
6.5	92	29	40	67	92
7	100	31	43	73	100

Figure 16: Graphic supplied by I Soils Ltd

Soils are difficult to research, complex chemically, and are ecosystems not fully understood by science, have variation across a field never mind a landscape. They are affected by weather and farm management and the plants grown.

The chemistry involved in soil science is above my knowledge base, the purpose of this appendix chapter is to highlight to farmers that caution is required when only using the Olsen P soil test as a requirement for further phosphorus applications. A further application of phosphorus on my farm will likely lead to additional soil reserves or pollution, not increased plant availability. Expert advice should be sought on soil testing, this is another demonstration of why nutrient accounting is essential alongside soil sample results.

I've spoken to many who are considered experts by their peers, I still find lack of agreement around balancing soil nutrients between (and for want of better terms) conventional scientists and regenerative farming approaches. What I can say conclusively is that every soil expert I interviewed all finished with similar sentiments. *"I have spent my career studying soil and I know less than 10% of what there is to know."*

Soil testing - knowing your base line:

It has occurred to me during my study that soil testing is rather rudimental, given such a small sample of 0.5 to 1 kg of soil is taken from several hundred tonnes in a field, which is analysed to estimate the nutrients which are plant-available. It's an historical snapshot and forms a base-line for calculating the additional nutrient requirement or nutrients in excess for any crop.

PH has easily the largest long-term impact on soil productivity and has a direct effect on the efficient uptake of all the other major nutrients.

When discussing the CO_2 burst test, (used to assess a soil's microbial activity during the growing season,) with a specialist fertiliser and soil conditioner manufacturer, they regularly observe, that the pH temporally falls during the growing period by around 0.4 PH. Rainfall, fertiliser and crop offtake all have a long-term acidifying effect, therefore targeting a winter soil test as high as pH 6.8 is recommended.

APPENDIX 6: COMPOSTING FARMYARD MANURE (FYM)

Interest in composting has increased significantly, largely due to its effectiveness in breaking down fibre in solid animal manures. The process reduces volume, mineralising and concentrating nutrients enhancing plant availability. However, its main drawback is the loss of volatile nitrogen into the atmosphere, particularly during turning. By adding a bacterial inoculum to a FYM heap and covering to create a Bokashi will avoid turning, helping to reduce nitrogen loss. Caution must be taken in a wet climate such as the UK to avoid pollution during mineralisation, via leaching and runoff.

Conclusion:

Creating a Bokashi should help reduce nitrogen loss and avoid the need for expensive compost turning equipment and time.

REFERENCES

Davids Attenborough's BBC documentary on the Life of Plants, in particular sub soil communication.

Crush, J. R., Nichols, S. N., Easton, H. S., Ouyang, L. & Hume, D. E. Comparisons between wild populations and bred perennial ryegrasses for root growth and root/shoot partitioning. *New Zeal. J. Agric. Res.* **52**, 161–169 (2009).

The following is a link to research on digestate separation technologies and their likely nutrient values.

https://pure.qub.ac.uk/en/publications/3c478565-7325-4b36-9a00-5ff187a9747b

https://pure.qub.ac.uk/files/518067264/PhD_Thesis_40061781.pdf

Understanding soil health using soil structure as a parameter, is AHDB's Visual Evaluation of Soil Structure (VESS) webpage, linked here. https://ahdb.org.uk/knowledge-library/how-to-assess-soil-structure .

Ammonia loss, worked example:

The UK has a cool climate so if we use the example of 40 g *(G.J. MONTENY1* AND J.W. ERISMAN Ammonia emission from dairy cow buildings: a review of measurement techniques, influencing factors and possibilities for reduction)* of ammonia a cow/day at 82% nitrogen for an average herd size of 200 cows housed year-round this would equate to losses of:

200 cows x 365 days x 0.04kg x 0.82%N =2394 kg/N

Figure 17: Hamiliton organic dairy farm, USA. Photo: author's own.

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