



International Fertiliser Society

POTATO NUTRITION – BUILDING FROM THE BASICS, ADDING THE BEST OF THE NEW

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SUMMARY

Achieving potato yield and quality requirements, requires a site-specific approach and a continued but more efficient use of fertilisers to achieve sustainable production. Excess nitrogen (N) supply can restrict yield but relationships between N uptake and yield, and between soil supply and N uptake, are not strong. Getting the rate of N application right is therefore an important, but not a simple, management decision. Data also suggest that lower N fertiliser rates could be used without impact on yield or potato tuber quality.

Rapid expansion of the potato canopy maximises capture of solar radiation driving total dry matter (DM) and tuber yields. N uptake supports canopy expansion but has limited effect on radiation use efficiency. As rates of applied N increase to the optimum, canopy persistence increases, with increases in radiation captured and DM yield. Indeterminate varieties partition less DM to tubers and, at high rates, N application can generate very large canopies, to the detriment of tuber production. Understanding the determinacy of varieties is now a key part of fertiliser recommendation systems. Peak rates of N uptake in potatoes occur only c. 30 days after emergence. Restrictions to early N uptake impact yield potential, giving only a very short window of opportunity to correct problems. To further optimise N management, more understanding is needed of: factors controlling the amount and timing of N uptake partitioning of N from the canopy to tubers, the role of continuing soil N uptake and how these are affected by management.

The C footprint associated with the field production of potatoes shows that 50-60% of greenhouse gas emissions is linked to N fertiliser use; with about half linked to nitrous oxide (N₂O) emissions in the field and half to fertiliser product emissions. Investment in improved technology within fertiliser production are reducing embedded C emissions in mineral N fertilisers. In parallel, commercial developments of waste-based fertilisers are allowing effective nutrient recycling.

The rapid and accurate measurement of the plant ionome, including micronutrients and their interactions, is increasing understanding of plant processes. For example, the role of calcium and boron, and their interactions in determining cell integrity is being revealed. Soil measurement can support a risk-based approach that identifies fields at highest risk of deficiency and enables agronomists to take action based on careful empirical observation even without a full understanding of the underlying mechanisms. Given the small amounts of micronutrients needed by crops, a focus on good soil structure and water supply, achieving effective rooting and getting pH right will largely address many of the issues.

More efficient N use will also help farms to achieve net zero for greenhouse emissions at farm scale, by reducing N₂O losses and improving nutrient use efficiency. Lower carbon fertilisers and best practice nutrient management must go hand in hand to address sustainability.

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Keywords: Nitrogen, canopy, determinacy, carbon footprint, fertiliser product emissions, calcium

1. INTRODUCTION

It is not possible to prescribe the nutritional requirements for the average potato crop as there is no such thing. Potatoes are not a single crop; both variety selection and field management are very distinctly shaped by intended end market (fresh-market potatoes, processed fried, wet or dry products, starch, seed etc). There are also interactions with soil and climate factors so that each crop will have specific requirements for nutrient supply to support both yield and tuber quality. In terms of yield, nitrogen (N) and potassium (K) are key nutrients, while tuber quality is determined, in particular, by the supply of K, calcium (Ca), and magnesium (Mg). Other macronutrients, such as phosphorus (P) and sulphur (S), and micronutrients, such as iron (Fe), zinc (Zn), boron (B), and manganese (Mn), also have essential functions in plant metabolism and, hence, also can impact yield and quality.

Optimising the use and recovery of nutrients applied in fertilisers applied at the recommended amount for the expected yield also requires that no factor which is within the control of the farmer or grower should adversely affect yield. These include the control of weeds, pests and diseases of both the above-ground plant and the root system wherever possible. Balanced nutrition is required; for example, inefficient use of N fertilisers can arise when there is too little plant-available P or K available in the soil. Poor soil structure can also reduce root growth and function which will reduce the crop's ability to access soil nutrients. Soil organic matter plays an important role in maintaining and improving soil structure.

For farmers, nutrient management (fertilisers and manure applications) is one of the main variable costs in potato production alongside seed and machinery/fuel. Inefficient applications of fertilisers have also been linked to water pollution (Davenport *et al.*, 2005). Recently the use of fertilisers has also come under increased scrutiny as part of the agricultural and food industries' response to the legal targets to reduce greenhouse gas (GHG) emissions by at least 100% of 1990 levels by 2050 (UK Climate Change Act, as amended 2019). These net zero targets will be met both by minimisation of emissions and adoption of schemes that balance any remaining necessary emissions with carbon sequestration activities, such as tree planting and use of carbon capture and storage technology. This challenge has led to a significant amount of fertiliser development and innovation.

2. UPDATING NITROGEN FERTILISER RECOMMENDATIONS FOR POTATOES - THE PRACTICAL APPLICATION OF PLANT PHYSIOLOGY

There has been an evolution in UK nitrogen (N) fertiliser recommendations for potatoes since the inception in 1967 of the overarching N recommendation system within the Ministry of Agriculture Reference Book 209 (RB209). The most recent incarnation of this advice is the AHDB Nutrient Management

Guide, still also called RB209. Initially, potato varieties were grouped as early, second early or maincrop reflecting the likely duration of growth and yield expectation. Grouping varieties to reflect determinacy and its impact on crop N dynamics was introduced into N recommendations in 2000 (Allison *et al.*, 2020). Work is currently underway to update the Nutrient Management Guide (Section 5 – Potatoes) facilitated by GB Potatoes. Allen and Scott (2001) summarised the key principles that should guide N fertiliser decision making on farm. These principles still hold today and are as follows:

1. N can enhance and, if in excess, restrict crop yield especially in early harvested crops. N management is therefore an important decision.
2. It is appealing to think that applying only a little N initially and then using a plant test to determine the need for subsequent applications would be the most efficient system; there is no proven methodology to do this in the UK
3. Use of a balance sheet approach for N supply and N uptake are compromised as the relationships between N uptake and yield, and between soil supply and N uptake, are not strong.
4. Varieties differ in their needs for N; the broad differences are well understood.
5. Previous cropping influences soil N supply.
6. Addition of organic manures affects the need for mineral fertiliser.
7. Final yield of potatoes is not strongly related to N uptake, hence yield prediction is not necessary. Any system that requires an estimate of final yield will tend to lead to the use of more N than is needed as few growers will use a yield lower than their best when predicting for the season ahead.

In this section, we review the development of N recommendations since the early 1980s based on work conducted by Cambridge University Farm (CUF) and Niab, funded by AHDB and CUPGRA.

2.1. Nitrogen response curves

Response experiments have been conducted to explore the link between productivity and N fertiliser application on arable crops since World War II and before (Crowther and Yates 1941). Results show huge variability in fertiliser effects, but they predominantly show that the applications of fertiliser N increase crop yields with diminishing increments in yield with each additional N increment. Modest yields are often achieved with no N: the higher the Soil Nitrogen Supply (SNS), the greater the potential yield where no N fertiliser is applied. Importantly, in potatoes, with high rates of N tuber yields may decrease with increasing N application: it is possible to apply too much N, particularly in indeterminate varieties (Meng *et al.*, 2025).

In order to interpret N response experiments, it is necessary to find a way of interpolating crop effects between the amounts of fertiliser that were tested. This is done by statistically fitting algebraically-defined N response curves to the yield data. Current approaches to curve fitting for cereal crops are described in detail by Sylvester-Bradley *et al.*, (2014). Good fitting relationships between yield and N

are possible but are usually delivered across a wide range of soils and seasons, and in such circumstances, the optimum can only be defined within ± 20 kg N/ha (Sylvester-Bradley *et al.*, 2014). Hence these empirically-derived curves are useful to create general advice, but do not provide site specific recommendations. Looking at all the data together from the work conducted by CUF and Niab, funded by AHDB and CUPGRA, also highlights that the relationship between tuber yield and the amount of N applied is complex. For example, at an application of 200 kg N/ha, yield can vary from c. 25 to 65 t/ha. Applying more N does not guarantee more yield. To make sense of this variation we need to understand how N affects the processes that drive yield formation.

2.2. Exploring the influence of nitrogen application on yield formation

Since the late 20th century, it has been understood that biomass production and subsequent yield formation is driven by the absorption of solar radiation by the crop. Monteith (1977) showed that this relationship between radiation absorbed and biomass production/formation is applicable across a wide range of crop types. Allen and Scott (1980) showed a close relationship between total dry matter (DM) production and radiation absorbed for a range of experimental potato crops. The slope of this line (unit yield per unit radiation absorbed) is the net radiation use efficiency (RUE). It is important to note that these relationships are for total DM production, not harvested (tuber) yield. Total DM production is driven by radiation absorption by the canopy (ground cover, GC) and how efficiently the radiation is used. Total DM production is then partitioned into production of tuber DM and haulm DM. The tuber DM is 'diluted' with water to give tuber FW yield. Hence, one major determinant of growth and a pre-requisite for large yields is rapid expansion of the potato canopy in spring. This allows the plants to maximise capture of the solar radiation required to convert carbon dioxide to sugars, which are then converted to other compounds constituting crop dry matter. Nitrogen is the major driver of leaf canopy expansion which it does by increasing cell division and cell expansion (Vos and van der Putten, 1998).

On 'fertile' sites, applying N has relatively little effect on canopy expansion. The main effect of N is to increase canopy persistence (i.e. delay senescence, Figure 1). Integrated GC (IGC) is a measure of canopy persistence and is highly correlated with radiation absorption and yield formation (Table 1). The law of diminishing returns applies here: the canopy is persisting, but into an environment with rapidly decreasing day length which is why radiation absorbed has a stronger relationship with yield than IGC alone, especially when comparing across different radiation environments.

Table 1. *Effect of nitrogen application rate on integrated ground cover, radiation absorption and yield (var. Brooke; Cambridge University Farm, 2009).*

N applied (kg N /ha)	Integrated GC (% days)	Radiation absorbed (TJ /ha)	Total FW yield (t /ha)
0	7515	12.59	55.6
125	9124	14.82	58.7
250	9748	15.36	59.4
375	10392	16.24	64.6

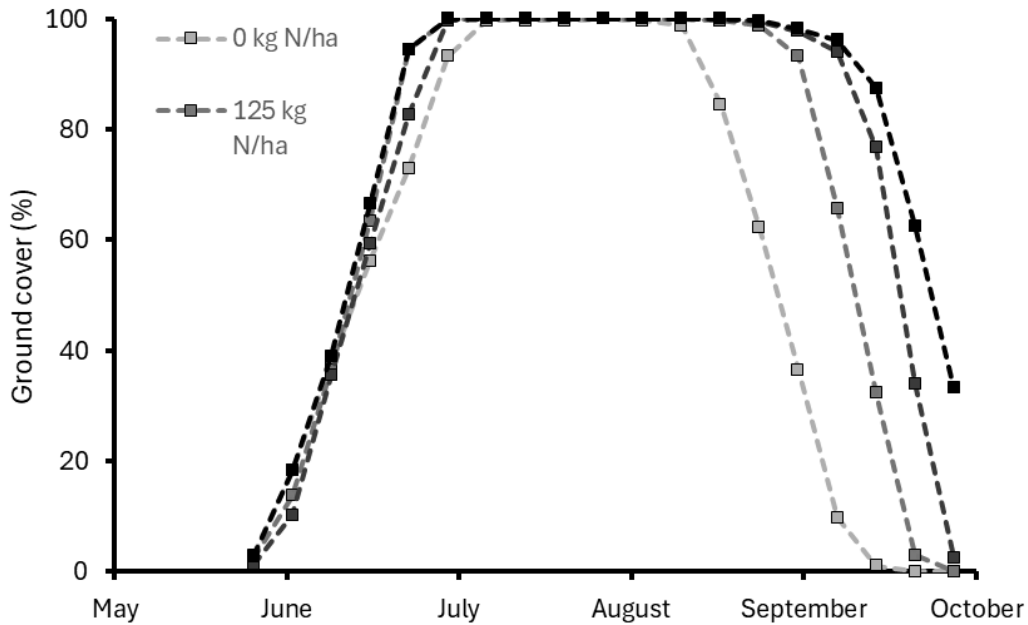


Figure 1. *Effect of nitrogen application rate on ground cover (var. Brooke; Cambridge University Farm, 2009).*

The radiation use efficiency (RUE) of crops is a measure of the conversion of intercepted radiation to biomass. Applying N has little effect on this relationship (Millard and Marshall, 1986). Firman and Allen (1988) also found that N had little effect on photosynthetic rate in individual potato leaves, confirming that increases in biomass production resulting from N application are achieved through effects on leaf area duration rather than RUE. Factors known to affect RUE are water stress, virus and temperature (respiration losses) and cultivar (genetic) effects (Stöckle and Kemanian, 2009). Using a much larger data set from many experimental crops, a limited effect of N uptake on RUE is also confirmed (Figure 2). Therefore, it is the impact of N on canopy persistence that is the main driver of changes in radiation captured and the overall biomass yield. This may be a sensible strategy for the crop: it is better to have a smaller canopy with high RUE than a larger one with a small RUE.

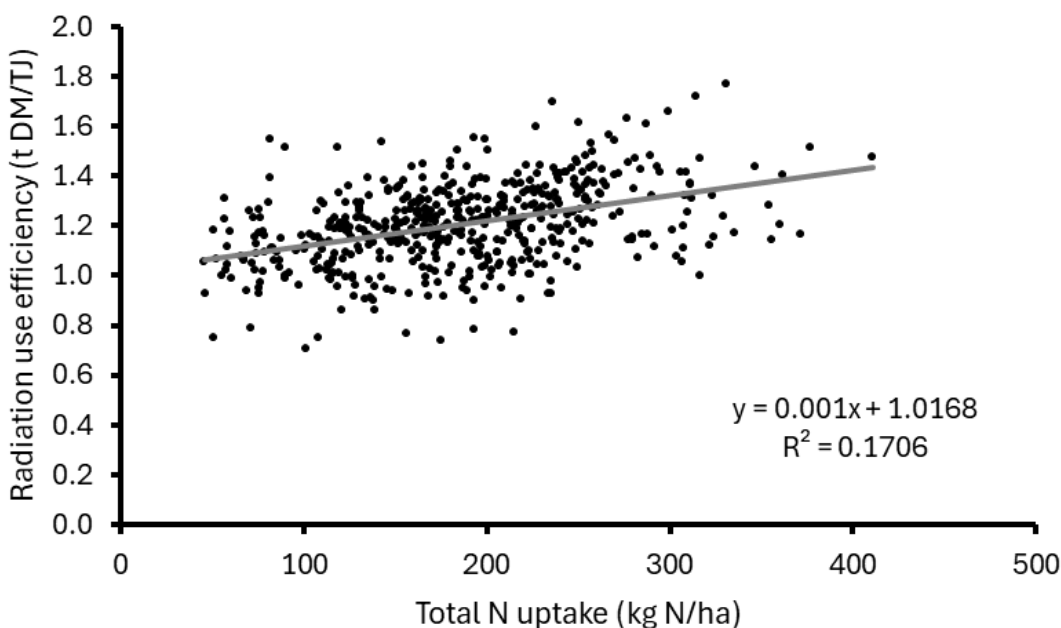


Figure 2. *Relationship between RUE and total N uptake (many varieties, Cambridge University Farm, 2004-2021, n=524).*

2.3. Impact of determinacy

Potato varieties vary in determinacy. A truly determinate potato variety is one that will cease leaf production after it has initiated its first flower and, conversely, an indeterminate variety will continue to produce tiers of leaves and flowers until curtailed by decreasing day length or frost (Allison *et al.*, 2020). In the UK, varieties are placed in one of four groups ranging from Group 1 (very determinate, e.g. Accord, Estima and Innovator) to Group 4 (very indeterminate, e.g. Cara, Markies and Royal). Data from two very contrasting varieties Estima (determinate) and Cara (indeterminate) demonstrate the difference that determinacy makes to N use and hence the importance of determinacy to N recommendations. The determinate variety, Estima, partitions more DM into tubers and Harvest Index (HI) is relatively insensitive to N application rate (Figure 3). In contrast the indeterminate variety, Cara, partitions less DM into tubers (HI only 70 % at the end of the season), and at high rates, N applications can generate very large canopies, reducing HI further. In short season crops, excessive N applications can negatively influence tuber yield, decreasing HI, e.g. for 90-day Cara, the total DM biomass is similar for 0 and 200 kg N/ha, but HI is 58% or 25%, respectively (Figure 3). In summary, HI changes with increasing N application rate differently in different varieties as a result of determinacy and this must underpin N recommendations.

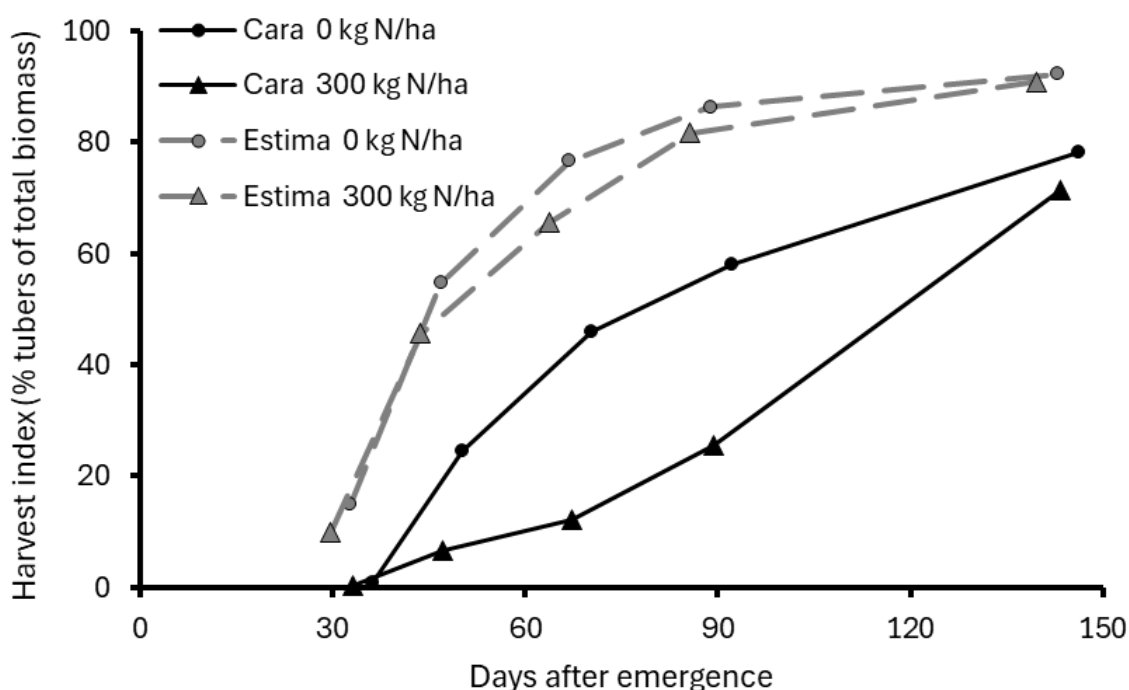


Figure 3. Effect of variety and nitrogen on harvest index (Cambridge University Farm, 2003).

2.4. Impact of nitrogen uptake patterns

Understanding the time course of when potato plants take up N is an important part of understanding how agronomic factors can affect yield potential. Analysis of published and experimental data show that most N is taken up

early in the season (Figure 4). Peak rate of N uptake occurs at *c.* 30 days after emergence (DAE), typically 5 kg N/ha/day. Barraclough (1986) showed that the maximum rate of N uptake in high yielding winter wheat crops was 2.8 kg N/ha/day, which is low compared to potatoes. At 30 DAE, ground cover is *c.* 50% and expanding at its fastest rate. Tubers have formed and are starting to demand N, whilst the root system is still relatively sparse. This highlights that any restriction on N uptake by roots will impact yield potential, and that there is only a very short window of opportunity to correct problems in N nutrition, even if they are detected early.

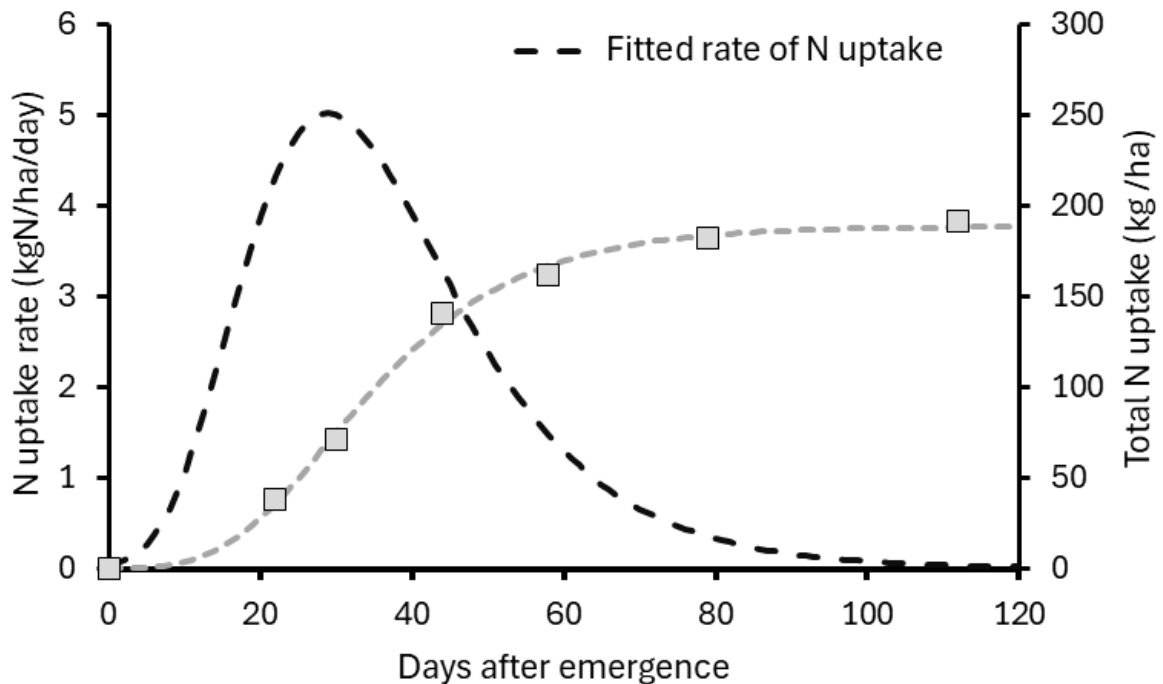


Figure 4. Total and rate of N uptake during the season (*Maris Piper*, fertiliser - 250 kg N/ha; redrawn from data from Millard & Marshall 1986).

Both total and tuber N uptake data are well described by radiation absorption. Total N uptake is exponential (initially rapid and then slows), but the rate at which tubers increase in N content is linear and relatively constant over the season (Figure 5). This is a key observation and warrants more work on how consistent it is between seasons and across different soils (fertility). The exception can be very indeterminate varieties (e.g. *Cara*) at high rates of N application, where there is yield reduction. More understanding is needed of the factors controlling partitioning of N from the canopy to tubers, the role of continuing soil N uptake and whether these are affected by management.

Around 55 DAE (or 4.6 TJ/ha of absorbed radiation), the rate of tuber N uptake exceeds total N uptake (Figure 6). At this point the haulm is directing a high proportion of photosynthate to the developing tubers and the N uptake pattern shows that the haulm becomes a net exporter of N into the tubers. Canopy persistence (as well as radiation absorption and yield formation) are controlled by how much N can be stored in the canopy and the rate at which N is transferred to tubers. This interacts with variety determinacy.

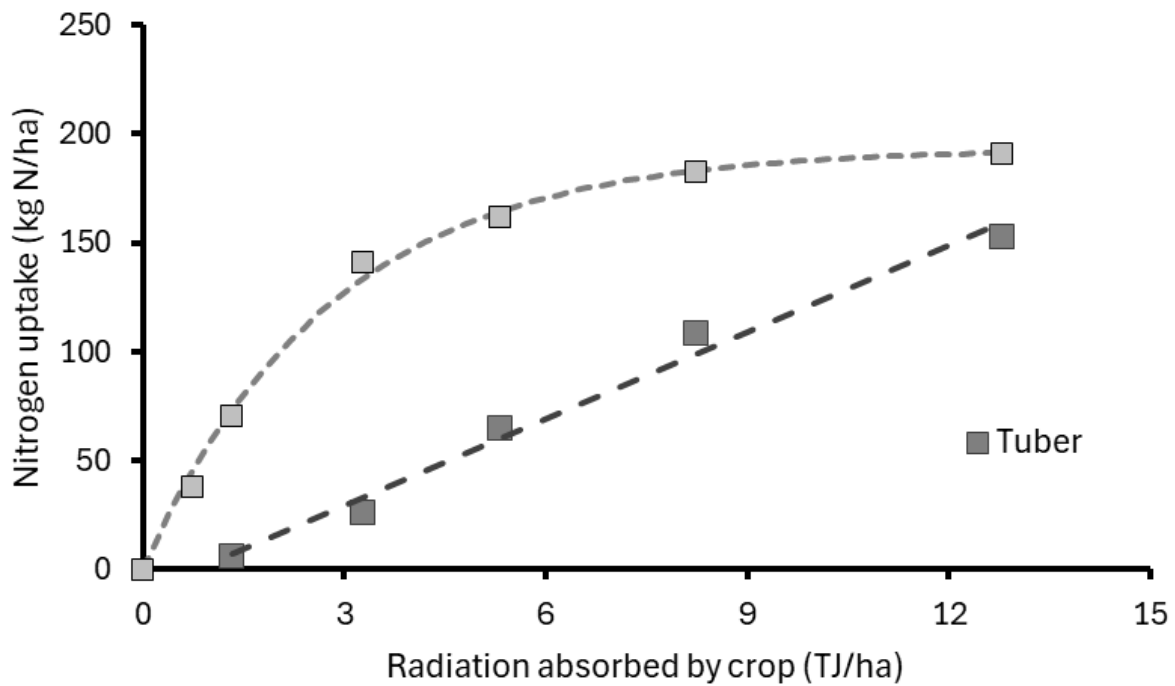


Figure 5. Relationship between N uptake and redistribution and radiation absorption (var. *Maris Piper*, fertiliser - 250 kg N/ha; redrawn from data from Millard & Marshall 1986).

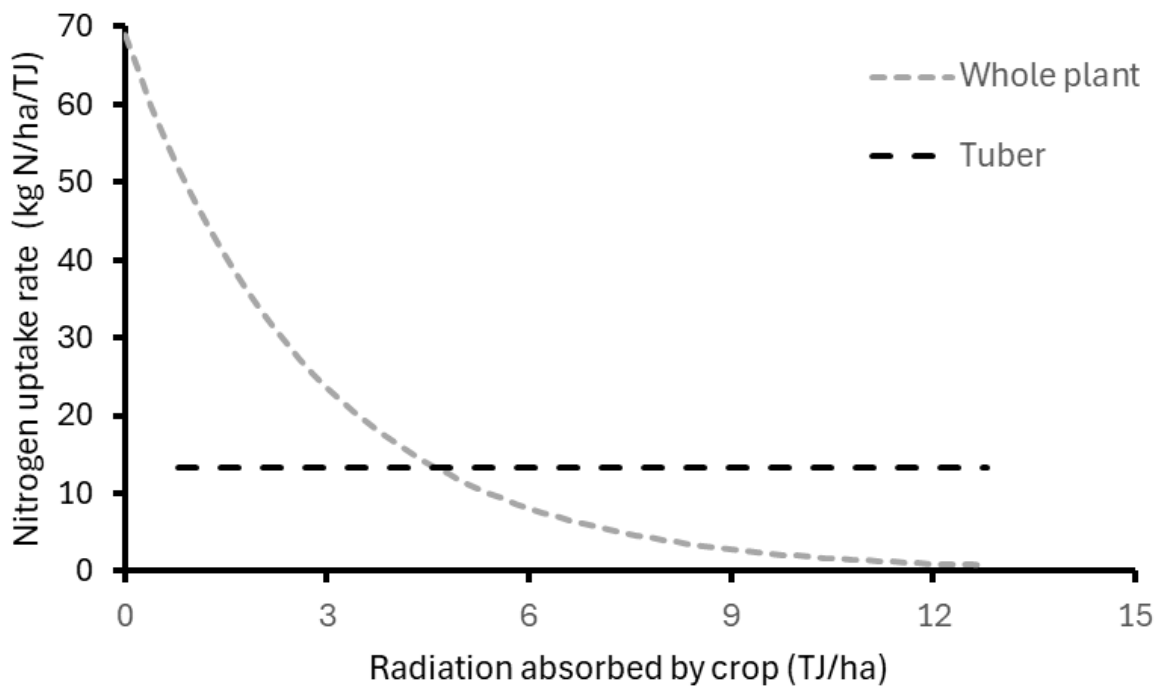


Figure 6. Relationship between N uptake and redistribution and radiation absorption (var. *Maris Piper*, fertiliser - 250 kg N/ha; redrawn from data from Millard & Marshall 1986).

An analogy of a fuel tank can be used. Estima (determinate) has a smaller canopy and hence a smaller fuel tank capacity than Cara (indeterminate). With Estima, it is important to fill it fully at the start of the journey (season) if we want the season length and yield to be maximised. With Cara, the potential fuel tank is very large, and if we fill it to its capacity and the journey (season) is shorter than expected, we leave fuel behind in the canopy and not

in the tubers. It takes longer to fill this indeterminate (big) fuel tank, so the tubers have a delay before they start to get their fuel.

N uptake rates are affected by soil conditions. The transport of nutrient to roots (by mass flow or diffusion) and root function are key in ensuring efficient N uptake. Here we show the results of some experiments where poor soil conditions were created deliberately by cultivating when soil was above the plastic limit, causing compaction, often a common occurrence in practice during planting in April. When soil conditions are good (freely rootable) and the crop is irrigated, total N uptake is large and the peak rate of N uptake is also rapid (>6 kg N/ha/day, Figure 7). When soil conditions are poor and the crop is unirrigated, total N uptake is reduced as is peak N uptake (<3 kg N/ha/day, Figure 7). Irrigation can help alleviate some of the problems caused by poor soil conditions, but not undo them completely (Figure 7). Such experiments also confirm that application of more fertiliser N also helped alleviate the effects of compaction, but is a very inefficient way of solving the problem (Stalham and Allison, 2012).

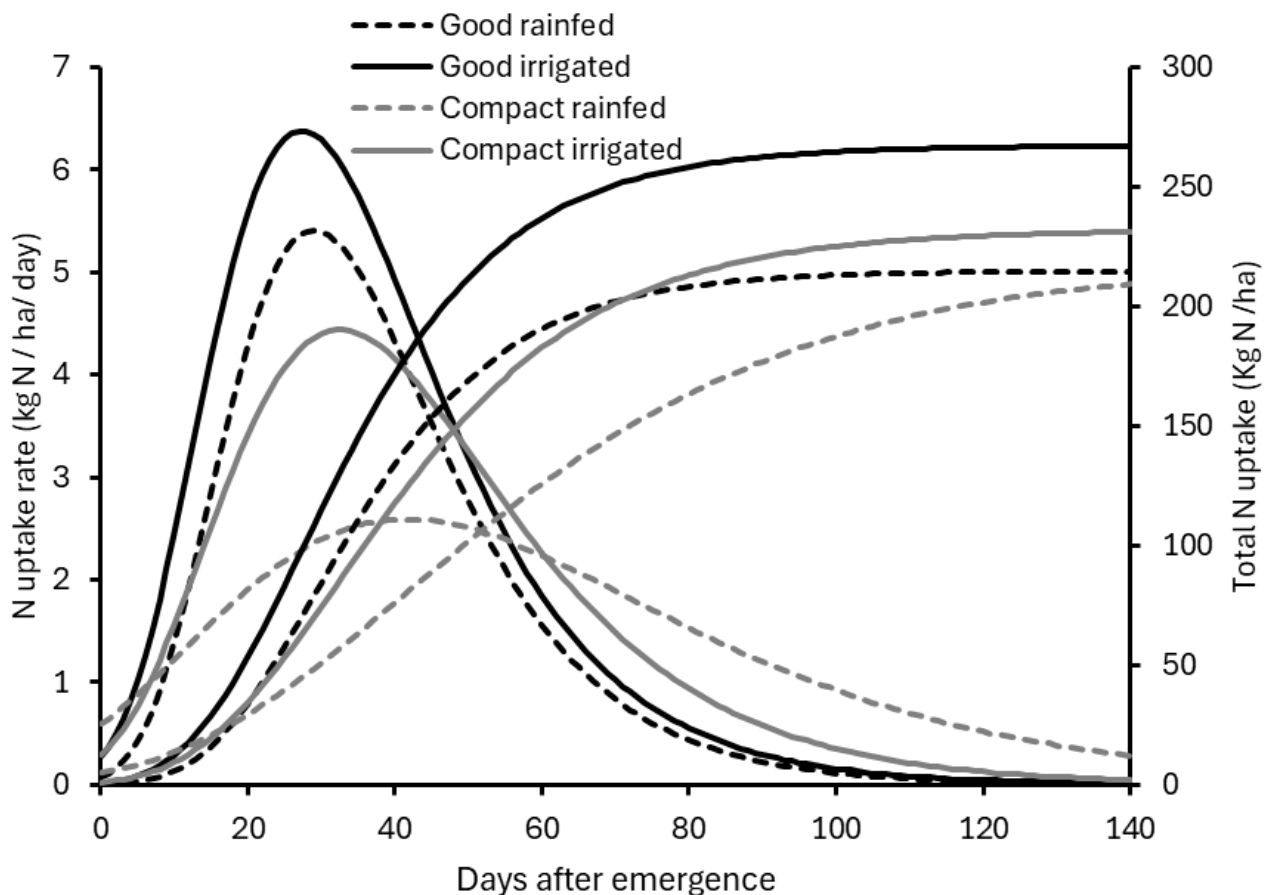


Figure 7. Effect of seedbed conditions and irrigation on N uptake (Cambridge University Farm, 2006, Maris Piper, 100 kg N/ha). Tuber yields were as follows:

Good seedbed conditions, irrigated – 67.7 t/ha;

Good seedbed conditions, rainfed – 47.7 t/ha;

Compact seedbed conditions, irrigated – 55.7 t/ha;

Compact seed bed conditions, rainfed – 45.9 t/ha.

These data confirm that rapid uptake of N early in the crop growth period is a key determinant of yield potential. Hence splitting N applications is unlikely to lead to improved N use efficiency for potatoes and may risk reducing N uptake rates during the key period of yield formation. However, we carried out experiments to show that placement of N fertiliser where the roots are most dense, not in furrow bottoms where roots are sparse and previously trafficked, may be appropriate and increase N use efficiency. Data collected by CUF showed that about of one third of a fertiliser application by top dressing across traditional potato ridges ends up in the wheeling where root density is sparse. Where the N fertiliser was collected and removed from the wheeling, there was no effect on yield, suggesting that it is surplus to requirements or even when it wasn't removed the crop couldn't access it; the same yield was achieved in treatments with and without the fertiliser removed (c. 17 kg N/ha of a 50 kg N/ha top dressing). Foliar N application or banded applications on top of flat beds may help improve efficiency of N use, but top-dressing traditional ridges wastes N.

2.5. Impacts of over-application of nitrogen

Data often suggest that some growers are applying too much N, or at least that lower N fertiliser rates could be used without impact on yield (Table 2). Sometimes excess N is applied as an act of insurance to mitigate against the risk of an under-fertilised crop since N is usually relatively cheap compared with the potatoes produced. Additionally, there are quality concerns related to under-fertilisation including risks of increased bruising and slower skin set. In a large study across the UK, a reduced N application rate by c. 30 kg N/ha increased tuber DM by 0.3% points, a very small difference (Table 2).

Table 2. *Effect of reducing N applications on tuber dry matter concentration. BPC & AHDB Grower Collaboration Project, 2007-2014.*

Average N applied (kg N/ha)	Yield (t FW/ha)	Tuber DM (%)
Standard 199 (n = 22)	56.4	21.8
Reduced 166 (n = 22)	61.0	22.1
Difference (standard error)	4.6 (1.52)	0.3 (0.167)
p value	0.002	0.090

It has been proposed that sub-optimal N application can increase bruising risk. Where bruising is tested on tubers from N response experiments, an increase in bruising at zero N application may be seen compared with higher rates of N fertiliser application. However, data collected for AHDB (Figure 8) showed that once the N rate is close to the optimum for yield, then small changes in N rate have little effect on bruising.

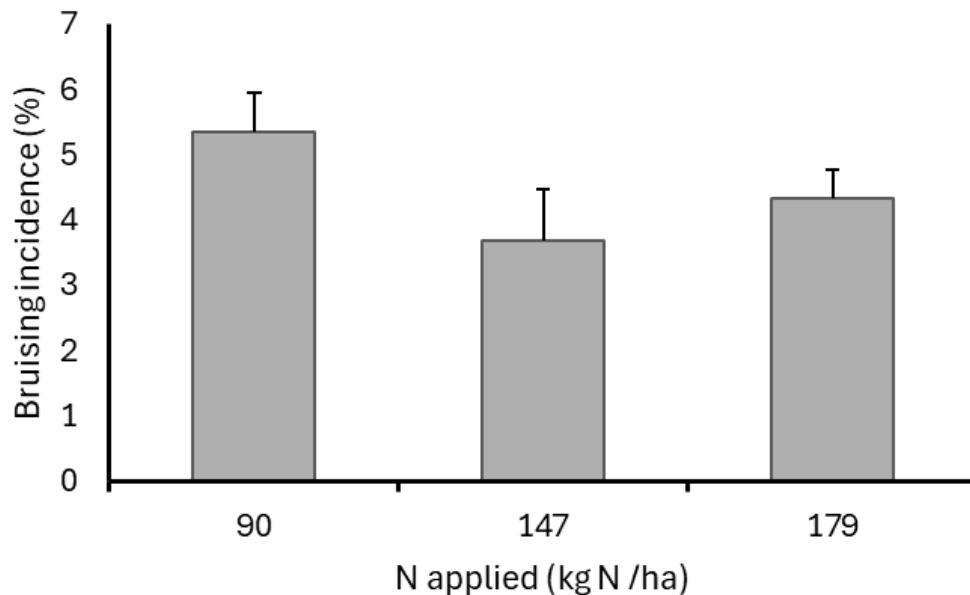


Figure 8. Effect of N rate on bruising incidence. AHDB SPot Scotland, 2018.

There are no clear indications that moderate reductions in N fertiliser applications would lead to measurable impacts on potato tuber quality. Hence it is now timely to re-examine the fertiliser recommendations for potatoes to take wider environmental impacts into account alongside market-driven economic factors.

3. WHAT NEW FERTILISER PRODUCTS SHOULD WE EXPECT (AND HOW CAN FARMERS EVALUATE THE BENEFIT)

Agricultural emissions (crop and livestock production) contribute 11.2% ($\pm 0.4\%$) of total greenhouse gas (GHG) emissions globally (Tubiello *et al.*, 2015). In an analysis of the C footprint associated with the field production of potatoes, 50-60% of GHG emissions can be directly linked to N fertilisation (Groves *et al.*, 2011). However, it is important to recognise that the total emissions associated with fertilisers result almost equally from their use in the field (fertiliser field emissions) and the high embedded energy cost and other nitrous oxide (N₂O) emissions arising from their manufacture (fertiliser product emissions).

The carbon footprint of mineral fertiliser production is assessed and reported using the Fertilizers Europe Carbon Footprint Calculator (CFC; Hoxha and Christensen, 2018). The European fertiliser industry developed the tool jointly as an industry standard. The tool is independently validated by DNV-GL and the Carbon Trust. Currently the calculator does not cover organic / organo-mineral fertilisers – this is an area that needs addressing. In this section, we summarise the main changes in N fertiliser technology than are expected to reach farms in the next few years and consider how farms should evaluate the benefit.

3.1. Lower carbon mineral fertilisers

The basis for producing nitrogen fertilisers such as urea, nitrates and NPK is ammonia. Ammonia is produced in industrial scale by combining nitrogen in the

air with hydrogen in natural gas, under high temperature and pressure (steam reforming) in the presence of catalysts. This process for producing ammonia is known as the 'Haber-Bosch' process. The side streams of the main production process (e.g. gases, nitrogen chemicals) are fully utilised by specialty fertiliser and industrial products businesses. However, the production process is energy intensive and also releases N_2O during nitric acid processing (Figure 9). In Europe, abatement of the N_2O from nitric acid production is achieved primarily through secondary (catalyst in burner) or tertiary (reactor in tail gas) technologies, achieving 80% to 99% reduction efficiencies. These methods are cost-effective, often with high return on investment, and are critical for reducing the potent N_2O emissions to effectively zero. Typically AN fertiliser production GHG emissions fall in the range 6-7 kg CO_2e /kg AN-N, but higher emissions are seen where no abatement is used currently, such as China. European production (2014 data), where the catalytic converter technology is fully deployed (abated systems), had a C footprint about half the typical (unabated) levels, at 3.42 kg CO_2e /kg AN-N.

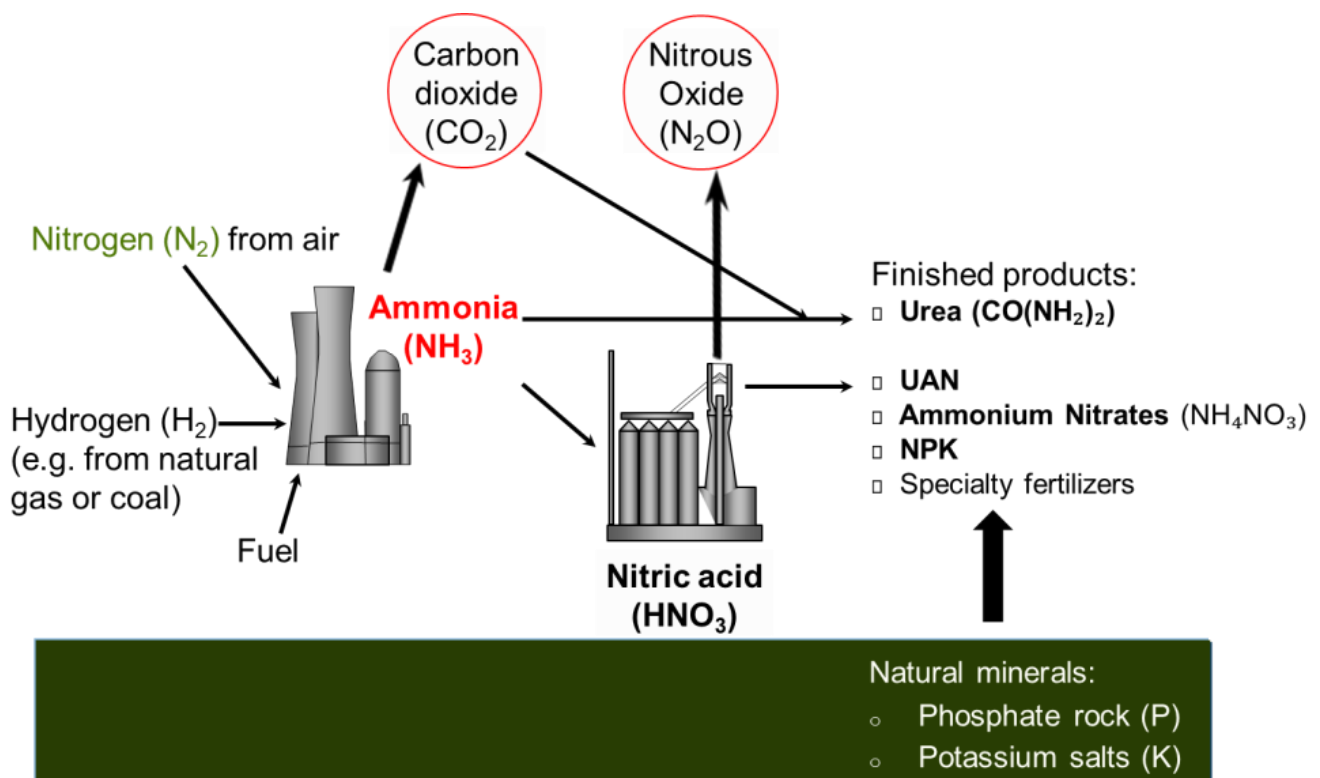


Figure 9: Schematic of the mineral fertiliser manufacturing process showing the associated GHG emissions which make up the fertiliser product emissions.

Further innovation is underway in the ammonia production step, with changes in both the processes and also in the source of the hydrogen for the process. The resulting ammonia products have become known by 'colours'. The most relevant for current fertiliser production are 'blue hydrogen' where carbon capture and storage technologies have been linked to the Haber Bosch process reducing the kg CO_2e /kg AN-N to 63% of those associated with current abated EU production. Further reductions in fertiliser product emissions would result where 'green hydrogen' is produced through electrolysis of biogas using renewable energy – such fertiliser products are

expected to carry small fertiliser product emissions (as some non-renewable resources will still be used); pilot systems are showing a reduction of kg CO_{2e}/kg AN-N to c. 20% of those associated with current EU production.

These lower carbon mineral fertiliser products are identical to classic mineral fertilisers when they are delivered to the farm. Hence no performance related trials are needed to optimise their use for potato (or other crops). On-farm introduction of these products may however also be associated with a system changes, e.g. solid or liquid fertiliser use, straights or compound fertilisers; where fertiliser systems are changing then on-farm optimisation trials may be required. Introduction of these fertiliser products is likely to be associated with a requirement at farm or supply chain level to reduce the size of the carbon footprint associated with the potato crop. Hence rather than focusing on crop performance, evaluations of different colours of AN are more likely to focus on the CO_{2e} reduction that can be achieved and how this is recognised within the supply chain. A key question for growers is where the cost of these changes and ownership of the carbon value fall. Currently the costs of choosing green fertilisers are high compared with current 'brown' ammonia-based fertilisers and hence it is likely that some of these adoption costs may need to be borne by other actors in the value chain.

3.2 Organic based / organo-mineral fertilisers

In parallel with the development of lower carbon fertilisers, there have also been some commercial developments in the development of waste-based fertilisers, leading to the development of commercially pelleted organo-mineral fertilisers where organic matter and nutrients are provided in an integrated way. This has been driven in part by the increase in anaerobic digestion facilities across the UK as well as the focus on reducing overall waste through development of re-use / recycling options. The key waste streams that are increasingly involved as feedstocks for organic-based fertilisers are livestock manures (largely intensive pig and poultry), anaerobic digestates, composts and blood / bone meal. As a result of the range of input materials—including mineral fertilisers—during co-pelleting, organo-mineral fertilisers show a wide range of nutrients, in a range of concentrations.

Organo-mineral fertilisers are very different from classic mineral fertilisers when they are delivered to farm. There will therefore be a need for performance related trials at the research level together with 'on-farm' trials to understand yield response, quality, nutrient use efficiency and patterns of nutrient release. On-farm introduction of these products is also very likely to be associated with a system changes as they are generally bulky materials compared with current mineral fertilisers and there may be a need for machinery investment. Antille (2001) used soil incubation, glasshouse, lysimeters and field studies to develop guidance for the use of one organo-mineral fertiliser type. More work is still needed to develop clear guidance for evaluation of the environmental impacts as well as the longer-term soil health benefits where organo-mineral fertilisers are used for the whole or part of a crop nutrition programme.

More data are also required for these products to quantify the CO_{2e} reduction that can be achieved and how this is recognised within the supply chain. As noted above, the Fertilizers Europe Carbon Footprint Calculator does not currently include organo-mineral fertilisers. Many of the C footprinting tools used on farms and within supply chains also do not include all (or sometimes any) of the available organo-mineral fertilisers. As discussed for low carbon mineral fertilisers, questions on ownership and collaboration across the supply chain with regard to the carbon value will apply.

3.3 Other innovations which may reduce fertiliser field emissions

There are two further innovations that are often considered when new fertilisers are discussed: nitrification inhibitors and biostimulants. These, together with a wide range of other factors, influence fertiliser field emissions. These are not the main focus here, but will be discussed briefly.

Inhibitors (nitrification or urease or both) are sometimes co-formulated with fertilisers or may be applied together with fertilisers. These technologies are not new and have been evaluated for use to reduce the risk of N losses and consequently enhance crop N uptake. Chen *et al.*, (2023) brought together the results of 26 meta-analyses of the effect of the wider group of enhanced efficiency N fertilisers (EEFs) which includes nitrification inhibitors, urease inhibitors, double inhibitors, and other controlled-release fertilisers - on the environment, nutrient use efficiency, soil fertility, and crop production in a range of cropping and pasture systems. They found that EEFs increased soil nutrients, crop yields, and N use efficiency, and reduced N leaching, emissions of greenhouse gases and air pollutants. So EEFs could maintain crop yields while reducing some of the negative environmental impacts of conventional mineral N fertilisers, but not all are win-wins and costs must be taken into account. Chen *et al.*, (2023) highlighted the need for research into the side effects of nitrification inhibitors on soil health, biodiversity, and water quality. It seems most likely that the widespread adoption of these products will be largely dependent on the role they can play in reducing Scope 3 emissions for across the wider food supply chain, as any cost benefit analyses for growers alone will be small as yield benefits are likely to be small and hard to prove.

According to the definition by the European Biostimulants Industry Council, plant biostimulants contain substance(s) and/or micro-organisms whose function when applied to plants or the rhizosphere is to stimulate natural processes to either enhance/benefit nutrient uptake, nutrient use efficiency, tolerance to abiotic stress or crop quality. These materials have no direct action against pests and therefore are not classified as pesticides. There are a range of different product types including seaweed extracts, humic substances, amino acids, and beneficial microbes. There is also a wide variety of different products within each of these categories, each often strongly differing in their mechanism of action. The EU Fertilising Products Regulation (EU 2019/1009) specifies that a plant biostimulant is a product which can demonstrate improvement in one (or more) of four categories: nutrient use efficiency, tolerance to abiotic stress, crop quality traits or availability of

nutrients in the soil and rhizosphere. This defines biostimulants by function, rather than composition, and creates a requirement for manufacturers to demonstrate to regulators and customers that product claims are justified. Abbott *et al.*, (2018) highlighted the lack of field-scale evidence of benefits for many biological amendments with potential to be used in agriculture. They noted that although considerable knowledge of the modes of action of many biological amendments is available, their performance under field conditions is usually less well understood. This can lead to proliferation of unsubstantiated assertions of efficacy. There is almost no evidence on the impacts of biostimulants (of any type) on direct GHG emissions. Hence the main mechanism proposed for the potential benefit of the use of biostimulants for GHG emissions is increased crop productivity with the same level of input use (N, fungicide inputs) or maintained productivity with lower inputs. Small benefits in NUE can be magnified when considered as emission impacts at the field and farm scale.

4. MICRONUTRIENTS - WHY THEY MATTER, NEW APPROACHES TO MEASURE AND MANAGE

In the preceding sections, the focus has largely been on N supply. However, achieving potato yield and quality requirements requires a site-specific approach, not only to macro-nutrient supply but one that also considers the relationship of these nutrients to each other and the wider range of micronutrients needed by the crop (Table 3). Micronutrients are defined by the FAO as: vitamins and minerals needed in very small amounts, whose impact on growth and health are critical, and where deficiency in any of them can cause severe and even life-threatening conditions. This definition is applied across human, animal and plant nutrition. It is also important to recognise that many micronutrients can also be toxic and that the optimum range can be very narrow. The individual physiological functions of each nutrient, as well as possible nutrient antagonisms and site-specific effects, are diverse and complex (Fan *et al.*, 2021).

Table 3. Roles of a range of key nutrients the physiological processes of the potato crop

Nutrient	Physiological role
Nitrogen	Component of chlorophyll, protein synthesis
Potassium	Stomatal regulation, control of cell turgor, carbohydrate allocation
Magnesium	Photosynthesis, enzyme regulation, carbohydrate partitioning
Phosphorus	Energy transfer, coenzyme synthesis
Calcium	Cell integrity and cell wall stability, secondary messenger
Sulphur	Synthesis of secondary compounds, protein synthesis
Iron	Chlorophyll formation, enzyme regulation
Zinc	Enzyme co-factor, cell membrane integrity
Manganese	Enzyme activation, cell elongation
Boron	Cell wall stability, phenol metabolism

Study of the whole mineral nutrient and trace element composition of an organism (the ionome) involves the quantitative and simultaneous measurement of the elemental composition of living organisms together with interactions between components and changes in this composition in response to physiological stimuli, developmental state, and genetic modifications (Salt *et al.*, 2008). A range of approaches have been proposed to evaluate ionic concentrations and ratios, however, despite the elucidation of a large number of positive and negative feedback loops and interactions in plants, the only point that scientists seem to agree on is that ionome homeostasis is very poorly understood (Fan *et al.*, 2021). It is likely that more rapid and accurate measurement will enable links to genetics and physiology to be explored more fully over the next decade, which may identify new factors driving yield and quality.

As a result of crop yield increases over the past 50-75 years, declining micronutrient concentrations in food products have been recorded largely as a result of yield dilution (Fan *et al.*, 2008); that is, the same amount of micronutrient taken up by the crop is diluted across the larger yield. In horticultural crops, micronutrient deficiencies and imbalances are also often detected through impacts on quality rather than yield. In this section, we explore how agronomists can combine understanding of soil and plant processes to develop site-specific micronutrient strategies for potato nutrition.

4.1 Presence and availability of micronutrients from soils

The amounts of micronutrients found in soil naturally are determined by the soil parent material and subsequent soil-forming processes. The initial trace element content of soils reflects the materials from which they form, but soil processes and landscape age introduce much variation even for soils formed on the same rock type (Jenkins and Wyn Jones, 1980). Parent materials differ widely in micronutrient content; modes of deposition and transport may vary; and weathering regimes can be different, so it is not surprising that trace element content, distribution, and availability can vary widely among soils within and between regions. A soil geochemical atlas is available for England and Wales (Rawlins *et al.*, 2012) which can help to highlight areas where topsoil contents of key micronutrients might be low (or excessively high). Graham (1978) calculated that the total soil pools of most micronutrients were equivalent to the amounts that would be removed by thousands of crops, whilst the pools are topped up in rain and dry deposition, as well as by co-inputs within manures and fertilisers. Hence soils are very unlikely to be mined of their micronutrients by agricultural crops. The micronutrient fingerprint of the soil will also change only very slowly over time, it is an inherent property of the soil, like soil texture.

Measurement of the micronutrient fingerprint through a detailed soil analysis will only be needed once but can then allow some targeting of interventions.

Micronutrient deficiencies occur in many cropping systems because the availability of any nutrient for crop uptake is always lower than the total pool of that nutrient in the soil. Plant roots take up nutrients directly from the soil solution which is then recharged from the more stable pools within the soil.

When they are in soil solution micronutrients are often in a free ionic form. Micronutrients are also present in solution as a chelate, adsorbed onto mineral or organic surfaces, present as precipitates or in lattice structures, or part of live or dead soil biomass. Micronutrients in each of these different pools is held more or less tightly; they have different bonding energy, and they are either partly available or completely unavailable to plants. The most important soil properties governing release of micronutrients to the soil solution are soil pH, redox conditions, cation exchange capacity, the activity of micro-organisms, soil structure and water content. Soil pH is sometimes called the master variable affecting micronutrient availability (Rengel, 2015). Soil tests using chemical extractions to predict micronutrient availability are only able to predict critical levels for a limited range of soils and must be interpreted for the particular crop (Sims and Johnson, 1991).

Crop micronutrient deficiency can be viewed as a combination of soil inefficiency in supplying micronutrients in plant-available forms and also plant inefficiency in micronutrient assimilation (White and Zasoski, 1999). The uptake of micronutrients by plants is influenced by the root architecture, the presence of mycorrhizal fungi and root physiology. Root architecture and more specifically the distribution of root hairs and mycorrhizal fungi determine the volume of soil from which micronutrients can be extracted, whereas root molecular and physiological mechanisms control the uptake of micronutrients into the root. Micronutrients enter plant cells as a result of active uptake processes mediated by transport proteins located in the plasma membrane of the cell. After minerals have been taken up by the cells of the root tissues, they are transferred to the xylem vessels for translocation to the shoots. Minerals are dissolved in water, either as free ions or complexed to low-molecular-weight organic molecules, and their transport in xylem vessels is dependent on the transport of water, which is directed from the roots to the shoots and which ends in the leaf. Small amounts may remain in root tissue, but the majority of nutrients are transported with water from roots to shoots to the sites of active photosynthesis. There may be some subsequent transport of nutrients with the transport of photosynthetic carbohydrates in the phloem, which are then directed from the photosynthetic leaves to plant tissues where carbohydrates are either consumed (growing tissues) or stored for later use (in seeds and tubers). Phloem transportation of minerals depends on the capacity of phloem loading which is different for different micronutrients. Where the focus is on micronutrient concentrations in tubers, i.e. tuber quality, then transport from leaves to tubers is a critically important step.

Alleviation of micronutrient deficiencies to improve crop yields or address crop quality issues is difficult due to the large temporal and spatial variation in availability of soil micronutrients. The easiest and most straightforward practice to correct micronutrient deficiency would be to apply micronutrient fertilisers to build up the amounts in soil. Soil application of fertiliser would also be economically more affordable. However, micronutrients are readily adsorbed on clay mineral and organic matter surfaces and, in addition, many of the soils used for potato production have low cation exchange capacity and

soil pH close to neutral or alkaline, leading to poor fertiliser use efficiency from soil-applied micronutrient fertilisers. Foliar application can provide a rapid correction of severe deficiencies commonly found during the early stages of growth and provides direct but temporary solutions to the problem. Foliar fertilisation is more effective than soil application, but needs careful management to balance the need to alleviate deficiency with the risk of toxicity (Khoshgoftarmanesh *et al.*, 2010).

Manganese (Mn) is the most widespread trace element deficiency in UK arable soils, affecting an estimated 60-70% of arable fields and causing significant yield losses. The first step for potato agronomists currently is to identify soils with a high risk of low Mn availability. Soil extractions are not used routinely. The amount of Mn in soil is expected to be low in soils with a high proportion of coarse sand and in soils with high levels of organic matter, especially peaty soils. Mn availability is also expected to be low where pH is high; soluble Mn forms are rapidly oxidised to insoluble forms under those conditions (Alejandro *et al.*, 2020). There are also interactions at the root surface that can reduce Mn uptake where P supply is high (Rengel, 2015); agronomists recognise that additional Mn may need to be supplied in fertiliser where available soil P is very high. In high-risk soils, given that Mn is readily locked up, the focus is on foliar application once the canopy has fully emerged (Rezende *et al.*, 2025). However, a number of applications may be needed since Mn does not remobilise from older leaves to Mn-deficient young leaves (Li *et al.*, 2017). Hence, in practice, Mn applications may be combined with blight sprays. Care is needed to take this approach only on high-risk soils, as potatoes are sensitive to Mn toxicity. Toxicity due to excess Mn supply can be seen as interveinal chlorosis (probably due to an induced iron deficiency) with significant inhibition in rooting (Marsh and Peterson, 1990).

4.2 Reducing tuber defects - is there a role for calcium and boron fertilisers?

Calcium (Ca) is required for structural roles in the cell wall and membranes, as a counter cation for inorganic and organic anions in the vacuole and as an intracellular messenger in the cytosol. For potatoes, ionic calcium is required for the normal functioning of calmodulin in non-specific plant defence reactions and is also an important trigger for tuberisation. However, even in crops with adequate calcium availability, periods of water stress can induce calcium deficiency, especially when requirements are high, such as at tuber initiation. Yield-limiting Ca deficiency is currently rare; however, deficiency symptoms are observed in a wide range of crops, in particular tissues, such as fruits and tubers, affecting quality (Shear 1975). White and Broadley (2003) provide a detailed summary of Ca uptake and translocation processes in plants highlighting that Ca cannot be remobilised and translocated *via* phloem which leads to these localised deficiencies. In potatoes, low concentrations of tuber Ca have been linked to increased occurrence of tuber blackspot, bruising and hollow heart. For example, Karlsson *et al.*, (2006) showed that an increase in tuber Ca from 100 to 250 mg Ca/kg resulted in a reduction of about 50% in the incidence of internal blackspot and bruising (in some but not all varieties). Palta (2010) highlighted a wide range of tuber quality traits that have been

improved through application of calcium. The work of Jiwan Palta and his research group has also highlighted genetic variation in response to Ca applications and revealed that some potato varieties have stolon and tuber roots which enable a continued supply of Ca to tubers. A good understanding of these physiological mechanisms is important to enable effective management to be developed. It is clear that a foliar application of Ca to the canopy will not be readily translocated to affect tuber Ca concentrations; hence an application of a soluble Ca fertiliser to moist soils in the tuber zone is critical where Ca supply from soil may be limiting; the critical period for uptake is between hook eye and 5mm tuber size (David Marks, pers. comm). The proportion of UK soils that are at risk of Ca deficiency will be much lower than for Mn, but higher risk sites and varieties should be able to be identified.

Application of boron (as soil-applied or foliar fertilisers) is common for sugar beet to reduce the risk of heart rot. Boron (B) is now known to provide a crosslinking mechanism to Rhamnogalacturonan-II (dRG-II) creating a dRG-II-borate complex that supports cell wall elasticity and function (Begum and Fry, 2023). In flowering plants, B is also key for transition from shoot meristems from vegetative to floral development. More recent research has highlighted the interlinked coregulation in plant tissues of B and phenols which would both lead to toxicity symptoms if either was in excess (Lewis, 2018). This co-regulation also indicates that there may be a role of B in mitigating the symptoms of bruising. Vera-Maldonado *et al.*, (2024) provided a review of the role of B in nutrient interactions and crop metabolism; this review noted the synergistic effects of Ca and B but concluded that more work is needed to develop clear guidance for fertilisation strategies. It is expected that high-risk soils for potato production would be similar to those identified for sugar beet, i.e. soils with a high proportion of coarse sand, high pH and low levels of organic matter. However, where sugar beet and potatoes occur within the same rotation, the B management strategy applied for sugar beet may meet the needs of the whole rotation.

5. CONCLUSIONS

Potato nutrition is likely to remain dependent on the continued but more efficient use of fertilisers, alongside the recycling of manures and other materials such as food wastes, and continuously improving good agronomic practices for all nutrients, not just N, P and K. Coupling the 4R nutrient management principles (right source, right time, right rate, right place) with soil health-improving and water protection practices (e.g. buffer strips) will also enable growers to provide nutrients when the crop needs them, as well as delivering the wider goals of enhanced soil health, and improved water quality. These approaches will also help farms to achieve net zero for GHG emissions at farm scale, by reducing N₂O losses and improving nutrient use efficiency at field scale.

Investment and technology in fertiliser production are helping to address the challenge of the embedded C emissions that are currently associated with N fertiliser production. These changes are essential if society wants to achieve a

balance in food security and environmental sustainability. More attention is needed to how and where the costs of implementation should be borne so that the most disadvantaged customers (both on farm and in retail) are not affected disproportionately. There is no silver bullet though – lower carbon fertilisers and best practice nutrient management must go hand in hand to address sustainability.

In potato crops, responses to N can be modest and inconsistent. In some response curves, it required 215 kg N/ha to obtain an extra 12.5 t/ha. If the response curve overturns, as is possible/likely in indeterminate varieties, yield is lost if too much N is applied. So, why do growers and agronomists tend to overestimate how much N to apply? Fear of being on wrong side of the optimum? Quality? More work is needed to help understand and then address the non-technical decision-making factors that affect nutrient management decisions. More work is also needed to improve understanding of the amount and timing of N uptake needed for an intended yield, together with the interactions with other management factors.

Management of micronutrients is, and will remain, complex. There are lot of interactions with soil type, between micronutrients and different impacts for different crops – where an agronomist starts to delve into the detail, it is not surprising that they can become overwhelmed. For many micronutrients we can identify ‘risky’ soils and then take targeted action; a quantitative risk assessment doesn’t need to be done every year, but it is a useful check where a grower takes on new ground. We expect that management for quality, rather than yield, will receive more attention in the future. Here there is more research needed to underpin our understanding of Ca and B and their interactions in determining cell integrity. A focus on identifying key situations where the risk is highest will allow agronomists to take action based on careful empirical observation even where the understanding of the underlying mechanisms remains incomplete. Given the small amounts of the micronutrients needed by crops, in the UK’s relatively young and unweathered soils (when compared with deep tropical weathered soils), it is very likely that a focus on good soil structure and water supply, achieving effective rooting and getting pH right - that is, good crop husbandry - will largely address many of the issues.

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