March 2019

Research Review

Ref: 11140047

A Review of Liming, pH and Common Scab Risk in Potatoes

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Report No.: 2019/6

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1. Abstract

This review examines the historic basis of current advice and recommendations for liming and gathers the most recent studies around the relationship between common scab, pH, lime application and calcium (Ca) in potatoes. Early sources of literature noted that the application of calcareous material to soils growing potatoes resulted in symptoms of common scab (caused predominantly by *Streptomyces scabiei*) and discouraged the use of such materials in production. This is reflected in current advice from AHDB and common practice (AHDB 2017a). Although more recent literature tend to identify high pH as a predominant factor for the symptoms of common scab, the results of pH and Ca are not always separated out, and confounding factors mean that results between seasons, cultivars and locations, can be inconsistent or contradictory.

Field experiments undertaken at Cambridge University Farm and by British Sugar, suggest that the application of lime and other Ca products such as gypsum, can give reductions in scab and improvements in marketable yield. It is suggested that lime application can increase pH above the upper tolerance for pathogenic *Streptomyces* (pH 7.5). Results using LimeX, a calcium by-product of sugar manufacture (Cogman, 2018), were mostly on soils of pH 6.6 to 8 where application increased pH beyond 7.5. On black fen soil where the starting pH was 5.4, LimeX at the highest rate only increased pH to 5.7 and had no significant effect on scab. Work conducted by Cambridge University Farm, showed reductions in scab with liming, but only on one site was pH increased beyond 7.5, with the other site increasing from a low pH (5.2) up to only pH 6.6 (Allison 2000a and Allison 2000b). Allison (2000a) also found that the largest dose of lime had a negative effect on yield. Whilst survey data indicate that only around 1 % of potato crops receive lime immediately ahead of planting, the more recent evidence suggests that liming of potato soils immediately ahead of production should not be a risk as long as pH is increased beyond a value of 7.5. Based on the trials and experiments listed above, a cost : benefit analysis using the scab-susceptible variety Maris Piper showed that a net benefit of £440-£1138/ha could result from liming from an improvement in marketable yield from a reduction in scab. However, Maris Piper is the most scab-susceptible variety commonly grown in the UK, and for varieties with much high resistance to scab (Groups 3 and 4 in Stalham, 2015), these financial benefits would be reduced by at least a magnitude. It should also be recognised that at high pH (> 7.5), Fe, Mn, B, Cu and Zn are less available than at the optimal pH 6.5.

The review also reports evidence for a non-pH induced change in scab susceptibility from gypsum application. Despite having a neutral or slight acidifying effect on soil pH, reductions in scab were observed by adding gypsum that could not be explained by Ca since other Ca products had no effect on scab. Gypsum is a well-known improvement agent for low organic matter clay soils, and this could have increased easily available water-holding capacity in the soil surrounding tubers, thereby aiding control of common scab using irrigation. Typically, gypsum improved the economic

performance of the crops through a reduction in scab more significantly than the addition of lime (£1154/ha for a gypsum application rate of 0.5 t/ha and £3042/ha for 5.0 t/ha).

Long-term studies of liming in the rotation generally show positive effects on yield and productivity due to the increased availability of nutrients at higher soil pH and the development of soil structure and improved root systems associated with liming. Increasing lime application and pH significantly over many years may have impacts on other crops in the rotation, including those that benefit from the application of lime, e.g. sugar beet, brassicas and carrots. In survey data from British Survey of Fertiliser Practice and NRM Ltd, a very high proportion of sugar beet crops receive lime ahead of drilling. In sugar beet, mild yield effects can be seen on mineral soils below pH 6.5 with more serious effects of soil acidity occurring on soils below pH 6.0. In brassicas, pH ≥7 may be most effective in reducing clubroot (*Plasmodiophora brassicae*) although the interaction of variety, nutrients, pH and inoculum load on clubroot development and expression can be greater than the liming induced changes. In carrot, cavity spot (*Pythium*) suppression through increasing pH with lime is not understood, and highly contrasting results are found between sites and between years. However, high pH and over-liming also increase the risk of boron (and to a lesser extent zinc) deficiency in oilseed rape and vegetables. All soils above pH 7.5 are at risk, with sandy soils with a pH above 6.5 and organic, peaty or marshland soils above pH 6 having a greater risk.

Several areas were identified where knowledge was lacking and where future research could aid crop performance and quality. These include:

- Using the British Geological Survey United Kingdom Soil Observatory Soil map viewer showing the distribution of soil pH to correlate with the location of actual potato crops to corroborate British Survey of Fertiliser Practice data
- Whether the current recommendations for liming ahead of potatoes are correct when pH is not increased above 7.5 as a result of liming and only need to be modified for high pH soils where brassicas or sugar beet are grown
- Confirmation of the upper and lower limits of pH tolerance for the pathogenic species isolated in the UK and the mechanisms of resistance/susceptibility to common scab
- Effect of calcium application on fry quality in both French fries and crisps.

2. Introduction

2.1. Current Practice

Church & Skinner (1985) reported that 29 % of the rotationally cropped area in England and Wales was below pH 6.5. Data obtained from re-sampling the same fields at intervals of 5 years from 1969 to 1983 showed that changes in the proportion of crops grown at different levels of pH had been small. The British Survey of Fertiliser Practice records the percentage of fields that farmers have applied lime to and recently there has been a decline in liming. The mean area of agricultural land limed for the 10 years prior to 2017 was 8.6 % for arable crops, 6.1 % for temporary grassland (less than 5 years old) and 3.2 % for permanent grassland (greater than 5 years) (DEFRA, 2016; Holland *et al*., 2018). Data covering the 11 years from 2007-2017 were extracted (Defra, 2007-2017). On average of those fields included in the survey, around 1 % of potato fields, 9 % of arable (tillage) fields and 24 % of sugar beet fields were limed immediately ahead of the respective crop, apparently demonstrating the very low proportion of liming occurring ahead of the potato crop (Table **1**). However, many potatoes are grown on rented land, and these data are largely not included in the survey.

Table 1. Use of lime, Great Britain from The British Survey of Fertiliser Practice 2007–2017 (DEFRA 2007 – 2017)

	Tillage - Total number sampled	Tillage - Fields limed	Potato - Total number sampled	Potato - Fields limed	Sugar beet - Total number sampled	Sugar beet - Fields limed	Tillage %	Potato %	Sugar beet %
2017	3948	342	86	1	81	20	8.7	1.2	24.7
2016	3848	325	30	1	63	15	8.4	3.3	23.8
2015	4547	452	104	2	100	25	9.9	1.9	25.0
2014	4743	449	117	0	132	33	9.5	0.0	25.0
2013	4428	360	107	0	117	33	8.1	0.0	28.2
2012	4753	467	128	0	142	23	9.8	0.0	16.2
2011	5105	452	134	0	132	27	8.9	0.0	20.5
2010	4826	471	140	2	105	31	9.8	1.4	29.5
2009	5309	468	149	1	131	28	8.8	0.7	21.4
2008	5280	513	111	0	135	30	9.7	0.0	22.2
2007	5267	469	150	4	167	42	8.9	2.7	25.1
						Mean	9.1	1.0	23.8

2.2. Current advice on liming

The Nutrient Management Guide (RB209) – Section 5 (Potatoes) (AHDB, 2017a) advises that liming immediately before potatoes should be avoided unless the soil pH is very low owing to the risk of common scab (and manganese deficiencies) at higher pH.

Current advice from AHDB (AHDB, 2010) for managing the risk of common scab identifies soil acidity as a risk factor for *S. scabiei*. The advice is that fertilisers or other materials that tend to increase the alkalinity of the soil should be avoided (including lime and poultry manure). This is based on the hypothesis that soils with low pH have a lower incidence of common scab. Following several interviews, this is also a commonly held view amongst growers, agronomists and fertiliser sales, distribution and application companies, but with little evidence behind the statement.

2.3. Common scab

Common scab disease of potatoes, caused mainly by *Streptomyces scabiei*, is an unsightly blemish disease that can affect any crop where tubers experience a dry surface during the critical stage in the 3-6 weeks following tuber initiation. The causal organism is widely distributed and is thus a threat in almost all soils. Cultivar resistance can effectively limit development of the disease, but in the driest years infection can occur even in highly resistant cultivars. The use of irrigation during the period of tuber initiation has provided an effective control measure where properly applied (Stalham, 2015). Lesions may be circular or angular and may coalesce into large irregular areas. Severity can range from sparse colourless, corky lenticels to dark brown, raised or pitted scabs covering the tuber surface. Common scab is a significant cause of marketable yield loss in the UK, costing the industry *c*. £3M during the 1990's (Anon 1998).

However, with increased restrictions on water use, alternative approaches to the control of common scab would be beneficial, but have not yet proven successful or consistent. It is widely documented that raising soil pH above neutral can increase the risk of infection and severity. It is routinely recommended to avoid increasing the pH of the soil by practices such as liming. Historic sources that hold this view are cited in Labruyere (1971), namely Thaxter (1892) and Staes (1895). Thaxter (1892) noted that application of calcareous material to soil resulted in severe scab, while Staes (1895) discouraged the use of such materials in potato cultivation. Davis *et al*. (1974 and 1976) cited Horsfall *et al*. (1954) and Eichinger (1957). Horsfall *et al*. (1954) said that increased soil calcium resulted in increased tuber calcium which was positively correlated with scab severity. Eichinger (1957) suggested that calcareous deposits altered the periderm cells of the peel, making areas with high calcium ion deposits highly susceptible to Streptomyces spp. The link between pH and calcium compounds is made in most of these papers, but is not separated out.

This review set out the context for the application of lime with regard to potatoes. It has collated experimental studies to summarise current understanding of the relationship between liming and soil pH, within the context of the risk of common scab, as well as highlighting knowledge gaps where future research is needed. Background information is needed to establish clear, accurate, advice for liming.

This review covers:

- The relationship between soil pH and calcium
- Historic basis of current advice and liming recommendations
- pH and scab
    - Whether it is possible in practice to increase pH beyond the tolerance range for *S. scabiei* (and other scab-eliciting pathogenic species and strains) by liming
    - Whether pH or Ca *per se* is a casual or controlling agent for scab
    - The effect of pH on populations of microflora antagonistic to pathogenic *Streptomyces*
    - The relationship to scab incidence following liming at different starting soil pH's
    - Factors other than pH in determining optimal conditions for growth of pathogenic and antagonistic *Streptomyces*
- Soil chemistry
    - The effect of clay content of soil, timing of Ca application and neutralising value (product and grade, e.g. Chambers 1985)
    - Application requirements for low and high reactivity products
    - Effect of large applications of K fertiliser increase on soil Ca availability
    - Poor nutrient availability at high pH (>7.5)
    - Effects of liming products on soil structure
- Rotational effects
    - The impact of liming policy on other crops (e.g. clubroot in Brassica, Ca-related disorders in vegetables, sugar beet sensitivity to low pH, B deficiency in sugar beet, carrots and Brassica at pH >6.5)
- The economics of the effect of liming policy on tuber yield and quality

The report by Elphinstone *et al*. (2004) was the last comprehensive review of non-water control measures for scab and new species (e.g. *S. acidiscabiei*) have been isolated since then. This review includes a search for information on other scab-eliciting *Streptomyces* species (including *S. turgidiscabies* and *S. acidiscabiei*) in the UK. The optimal pH ranges of these species are discussed.

The role of calcium on internal defects (internal brown spot and hollow heart) and the influence of tissue calcium concentration on storage-related aspects (e.g. periderm thickness, soft-rot breakdown, bruising or textural changes), whilst beyond the scope of this review, is also briefly summarised.

2.4. The relationship between soil pH and calcium

Two adsorbed cations are largely responsible for soil acidity: hydrogen and aluminium. If adsorbed hydrogen and aluminium are replaced from acids soils by cations such as calcium (Ca), magnesium (Mg) and potassium (K), the hydrogen ion concentration in the soil solution will decrease. The concentration of hydroxyl ions will simultaneously increase since there is an inverse relationship between hydrogen and hydroxyl ions. A direct correlation exists between the percentage base saturation of a soil and its pH. As the base saturation is reduced as a result of the loss in drainage of calcium and other metallic constituents, the pH is lowered in a more or less definite proportion. Thus the ‘base-forming’ cations become sources of hydroxyl ions merely by replacing the adsorbed hydrogen. Buffering capacity is the ability to resist change in pH of the soil solution.

2.4.1. **Measurement of soil pH**

Soil pH is defined as the negative logarithm of the hydrogen ion concentration in the soil solution, so pH 6 is 10 times more acidic than pH 7. However, the salt concentration in the soil solution and the ratio of soil : water volume affects the measurement of pH. The most commonly employed methods to determine a soil's LR involve soil-lime incubations or soil-base titrations; however, because of the time required to reach equilibrium the methods are very time consuming. The fact that buffer-pH methods provide a rapid and convenient means of estimating soil LR values, compared with the incubation and titration procedures, has meant that several such methods have been proposed over the years.

Measurement of soil pH is the easiest and most commonly performed of all soil analyses and is one of the most indicative measurements of the likely chemical and microbiological properties of a soil (Breitenbreck & Bremner, 1984). However, measurements can be highly ambiguous. Two factors appreciably influencing soil pH measurements are the soil: solution ratio and the equilibrium salt concentration. Increasing either factor normally decreases the measured soil pH (Bohn *et al*., 1979). Avery and Bascomb (1974) recommended a standard soil water or 0.01M $CaCl_2$ ratio of 1:2.5 (w/v). However, ratios of 1:1, 1:2 or even 1:10 are also commonly used (McLean, 1973; Mehlich, 1976).

The dependence of measured soil pH on salt concentration, which is continuously varying in natural soil, can be reduced by making all the measurements in a salt solution that is sufficiently strong to swamp these natural changes (Russell, 1973). Schofield & Taylor (1955) proposed the use of 0.01M $CaCl_2$ for temperate soils on the grounds that it approximates to the Ca concentration in the soil solution, equalizes ionic strength and reduces the importance of the soil:solution ratio, when measuring pH. Breitenbeck & Bremner (1984) also reported pH values measured 'in situ' in the field agreeing closely with those obtained using 0.01M $CaCl_2$ (1:2 w/v ratio). The pH in 0.01M $CaCl_2$ is typically 0.5-0.9 units lower than that measured in water. This can be explained by the salt-displacing exchangeable hydrogen and aluminium, the suppression of electrical double layers and the subsequent hydrolysis of aluminium in the soil solution lowering the pH (Coleman & Thomas, 1967).

2.4.2. **Buffering capacity**

For soils below pH 7, rainfall, root uptake of cations with release of balancing hydrogen ions, leaching of calcium and use of some nitrogen fertilisers will acidify soil. Such acidifying processes rarely affect calcareous soils. Removal of hydrogen ions from the soil solution results in their being largely replaced from the reserve acidity held on the soil colloids. Soil acidity and the nutritional conditions that accompany it result when there is a deficiency of absorbed metallic cations relative to hydrogen. Replacing the hydrogen is commonly done by adding oxides, hydroxides or carbonates of calcium or magnesium, colloquially known as agricultural limes.

If just sufficient liming material is added to neutralize the hydrogen ions in the soil solution, more hydrogen ions move out into the solution, resulting in a negligible rise in pH, unless enough lime is added to deplete appreciably the reserve acidity. This resistance to pH change is important in preventing a rapid lowering of the pH of soils. The buffer capacity of a soil lies in the absorbed cations of the soil complex: hydrogen and aluminium ions, together with the absorbed metallic cations, not only indirectly control the pH of the soil solution, but also determine the quantity of lime necessary to bring about a given change. The buffering capacity of a soil is closely related to its cation exchange capacity (CEC), therefore influenced significantly by soil texture (clay content) and OM. Sandy soils have lower CEC than clays and 1:1-type clays have appreciably lower CEC than 2:1-type clays. Increased organic matter raises CEC.

2.5. Previous reviews

Two key reviews summarise the background to recommendations for the application of calcium to potatoes, with particular reference to common scab: Elphinstone *et al*. (2004) and Lambert & Manzer (1991). These reviews discuss the long-held relationship between scab and pH, and the contention over the role of calcium in scab development. In terms of distinguishing between the effects of pH on common scab and the specific role of calcium, Elphinstone *et al.* (2004) did not consider calcium per se to have any effect on common scab.

Elphinstone *et al*. (2004) included a review of the different bacteria species which give rise to common scab lesions. Those which may be found or are active under different environmental conditions, include the *S. scabiei* complex (active in neutral and more alkaline conditions) and *S. acidiscabiei* (active down to pH 4.5, Lambert & Loria, 1989). Elphinstone *et al.* (2004) cited Natsume *et al*. (2001) to highlight that production of the scab toxin thaxtomin A may itself be affected by pH (as well as temperature and more relevantly the availability of calcium and phosphate) in both *S. scabiei* and *S. acidiscabiei*.

Elphinstone *et al*. (2004) concluded that acidophilous scab species are less common in the UK and that common scab incidence was related to pH not calcium concentration. In order to reduce scab incidence, they therefore recommended that soil pH should be regulated by adding acid-producing fertilisers (such as sulphur powder or ammonium sulphate) and by avoiding alkaline products such as lime or manure. This conclusion and resulting recommendation was based on reviews examining the suppression of common scab at low (<5.2) pH (Waksman, 1950; Lapwood, 1973; Brenchley & Wilcox, 1979; Keinath & Loria, 1989; Lambert & Manzer, 1991; Lindholm *et al*., 1997; Mizuno *et al*., 1998; Lacey & Wilson, 2001; Loria, 2001; Park *et al*., 2002).

Lambert & Manzer (1991) started with the hypothesis that liming of low pH soils increased common scab, quoting Lambert & Loria (1989) and Keinath & Loria (1989). Following the findings of their own experiments with dolomitic lime and gypsum, they found that scab incidence (*S. scabiei*) was correlated with soil pH rather than calcium concentration in the soil, healthy periderm or medullary tissue. The authors concluded that scab infection was determined by soil hydrogen ion concentration rather than by soil calcium concentration, the ratio of calcium to other elements or the effect of calcium on scab resistance in the tuber (Blodgett & Cowan, 1935; Terman *et al*., 1948; Horsfall *et al*., 1954; Houghland & Cash, 1956; Doyle & McLean, 1960; Davis *et al*., 1974; Davis *et al*., 1976; Goto, 1985).

Previous studies concluding that high calcium levels (in the absence of changes in pH) may cause scab are disputed by Lambert & Manzer (1991). Lambert & Manzer argue that Horsfall *et al*. (1954) did not provide sufficient evidence and suggested there may have been a degree of experimental error. With respect to Goto (1985), Lambert & Manzer suggest that it may not have been *S. scabiei* that was causing the scab, and reanalysing the data found that they supported the pH theory once the covariance of calcium with pH was taken into account.

The Davis *et al*. studies (1974; 1976), Lambert & Manzer argue, conflate the positive effects of irrigation on scab, and also the increased concentration of calcium in the periderm in infected tissues, which could be a side effect of the disease rather than a cause.

RB209 research review database

The AHDB Nutrient Management Guide (RB209) update conducted by Allison & Sagoo, (2016) included a search for relevant recent literature on calcium using the search terms ‘calcium AND fertili*er AND potato*’ 2009-2016 for the locations UK (including England and Scotland), Ireland, France, Belgium, Netherlands, Germany, Denmark, Finland, Sweden and Norway. The academic literature search yielded no articles relating to calcium fertilisers or scab. Experimental data used in the review relating to calcium and scab are discussed later.

The outcomes of the review for RB209 (Allison & Sagoo, 2016) in relation to calcium were:

- New recommendation: due to evidence from CUPGRA and British Sugar-funded experiments, the review suggested the removal of the warning relating to liming before potato crops.
- Suggested areas for future research: in light of data submitted by CUPGRA and British Sugar, the review suggested that application of calcium-containing materials may reduce the incidence of common scab, not increase it. The review suggested that it would be useful to conduct a larger review of available data (to include data under-pinning current recommendations to avoid applications of liming materials) with new experimental/survey work where necessary.

2.6. Liming materials

The most common liming materials are burnt lime or quicklime, slaked lime or carbonates of lime (Brady, 1974). Burnt lime is produced by heating limestone in large commercial kilns and ranges from 85-98 % purity, with 95 % being used as an average. Slaked lime is produced by adding water to burnt lime and is typically 95-96 % pure. There are a number of sources of carbonate of lime, mostly commonly ground or pulverized limestone. The calcite form contains mostly calcium carbonate, whilst the dolomitic form contains predominantly calcium magnesium carbonate. Most crushed limestone is a mixture of calcic and dolomitic. The range in purity is greater than burnt or slaked lime but averages 94 %.

Holland *et al*. (2018) conducted a review into the impact of liming on soils in the UK. Ground limestone ($CaCO_3$) is the most common liming material for arable crops and grassland followed by dolomitic lime (magnesian limestone, $CaMg(CO_3)_2$) (Defra, 2017). Other materials used include slaked lime ($Ca(OH)_2$), sugar beet lime, gypsum and some calcium-containing organic fertilisers.

Two quality characteristics are used for liming materials, neutralizing value (NV), partly determined by the chemical composition and effective CaO content (ECC), and particle size (finer material being more effective in increasing pH (Bailey *et al*., 1989; Alvarez *et al*., 2009; Higgins *et al*., 2012)). The NV is the ability of different products to increase pH. Goulding (2016) describes this as the amount of acidity that it will neutralise based on a reaction with hydrochloric acid (Table **2**).

Table 2. The neutralizing value of various liming materials expressed as a weight percentage of pure lime ($CaCO_3$) adapted from Bolan *et al*. (2003) (Goulding, 2016, p. 395)

Liming material	**Chemical formula**	**Neutralising value (%)**
Burnt lime	CaO	179.0
Slaked lime	$Ca(OH)_2$	136.0
Dolomitic lime	$CaMg(CO_3)_2$	109.0
Lime	*$CaCO_3$*	*100.0*
Basic slag	$CaSiO_3$	86.0
Phosphogypsum	$CaSO_4.2H_2O$	0.3
Mined gypsum	$CaSO_4.2H_2O$	12.4
Flue gas desulphurised gypsum	$CaSO_4.2H_2O$	0.1
Coal fly ash		Variable

Italicised text shows lime as the reference against which other acid neutralising materials are compared.

3. Liming, pH and common scab

3.1. Experimental studies since 2004 on the relationship between scab, pH and calcium

Recent reviews on common scab include Dees & Wanner (2012) and Braun *et al*. (2017). No recent papers challenging pH as a control method for scab were reported in these reviews, or were found in literature searches (although all sources highlight that it is an incomplete and variable control). The mode of action of scab control is potentially related to:

i) Suppression of pathogen survival and / or growth caused by the pH of the growing media alone;

ii) Suppression at these pH values due to the action of antagonistic microflora (Sturz *et al*., 2004; Sturz e*t al* ., 2005);

iii) Suppression of the pathogen due to nutrient availability to the pathogen (Kontro *et al*., 2005).

3.2. pH tolerances of scab-causing *Streptomyces* species

Three species of scab-causing *Streptomyces* species are confirmed as occurring in the UK: *S. scabiei*, *S. acidiscabiei* and *S. turgidiscabiei* (Thwaites *et al*., 2010). *Streptomyces scabiei* is described as requiring a minimum pH of 5.0 (Lambert & Loria, 1989) and as occurring in very high populations or causing severe scab in soils up to pH 7.5 (Powelson & Rowe, 2008 cited by Braun *et al*., 2017; Table **3**). Lambert & Loria (1989) and Anderson & Wellington (2001) describe *Streptomyces acidiscabiei* as having a range from pH 4.0 up to 5.2 (Table **3**). Miyajima *et al*. (1998) describe *Streptomyces turgidiscabiei* as having a minimum pH requirement of 4.5 (Table **3**).

A fourth species, *S. europaeiscabiei*, described in Bouchek-Mechiche *et al*. (2000), is confirmed in mainland Europe, USA and Canada, but not confirmed in the UK. Flores-Gonzalez *et al*. (2008) argue that (based on DNA-DNA hybridization rates and 16–23S rDNA sequencing), *S. scabiei* is genetically at least three different species that cannot be distinguished phenotypically: *S. scabiei*, *S. europaeiscabiei* and *S. stelliscabiei*. This is also supported by previous work that they cite, including Healy & Lambert (1991); Takeuchi *et al*. (1996); Song *et al*. (2004) and Bouchek-Mechiche *et al*. (2006). *Streptomyces europaeiscabiei* has been previously implicated in netted scab (Pasco *et al*., 2005 and Bouchek-Mechiche *et al*., 2006), along with *S. reticuliscabiei*, but has also been found in common scab lesions and *S. europaeiscabiei* is increasingly implicated in France, the USA and more widely as contributing significantly to the incidence of common scab (Bouchek-Mechiche *et al*., 2000; Wanner, 2007; Flores-Gonzalez *et al*., 2008; and Dees *et al*., 2012a and 2012b). However, a specific pH tolerance range for *S. europaeiscabiei* was not found in the literature.

Table 3. Summary of the pH ranges of scab species occurring in the UK

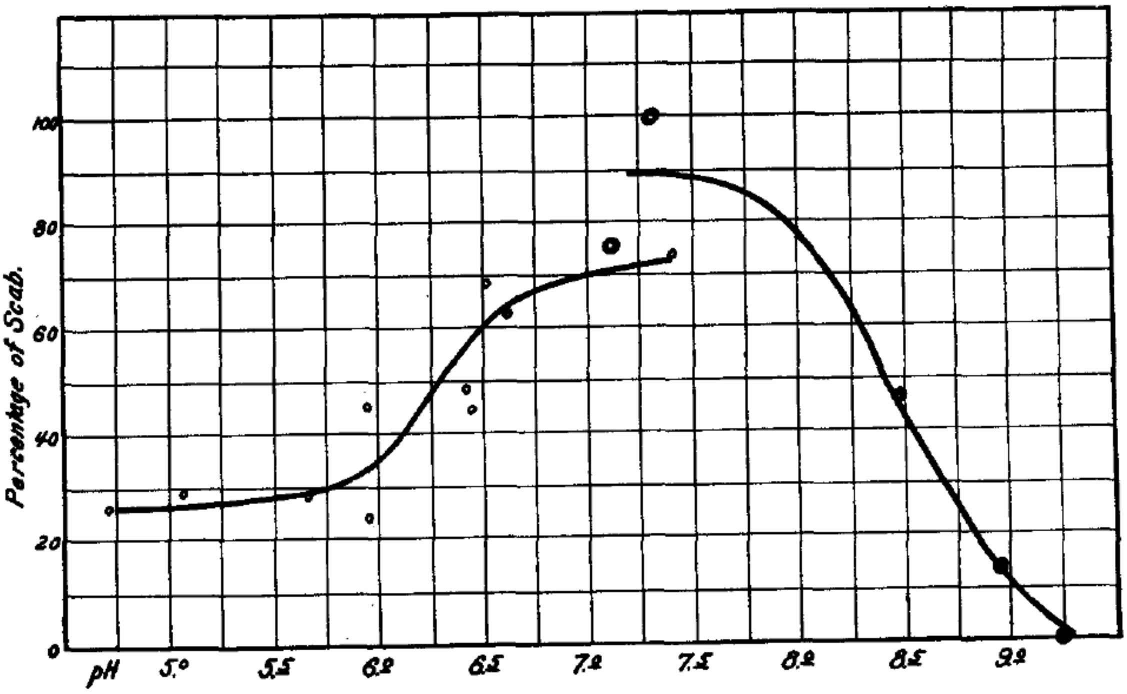
***Streptomyces* species**	**Lower pH tolerance**	**Upper pH tolerance**
S. scabiei	5.0	7.5
S. acidiscabiei	4.0	5.2
S. turgidiscabiei	4.5	-
S. europaeiscabiei	-	-

3.3. Using lime to increase pH

Assuming pH is a key factor for the occurrence or expression of scab symptoms, increasing soil pH to beyond the tolerance maximum of the scab-causing organism could contribute towards an effective control of the pathogen. This would mean pH 5.2 for *S. acidiscabiei* and *S. turgidiscabiei*, and > pH 7.5 for *S. scabiei* and *S. europaeiscabiei* (assuming the latter has a similar range). The central range between pH 4.0 and 7.5 includes all of the scab-causing species found in the UK, with *S. scabiei* being the dominant scab-causing organisms in the UK. If soil pH was not raised substantially above 7.5, increasing the alkalinity could potentially move pH into the risk zone. Identification of the starting pH and scab organism present would impact the target pH and whether this could feasibly (and economically) be achieved through the application of lime.

Blodgett & Cowan (1935) showed that common scab was more effectively inhibited by very high pH than very low which possibly gives an indication as to why avoiding lime before potatoes on acid soils can often fail to give a satisfactory result (Figure **1**). Environmental factors, such as pH, soil moisture, and soil microbial flora, in combination with potato cultivar and virulence of the pathogen, make management of common scab a difficult task.

Figure 1. Curves showing the relation of average pH to percentage of scabby tubers for the results of experiments. Curve from pH 4.7 to 7.4 on LHS. Curve pH 7.2 to 9.3 on RHS. Source: Blodgett & Cowan (1935).



3.4. Increases in pH achieved using lime

Alvarez *et al*. (2009) examined high aluminium acidic soils in Galicia, Spain, with a view to investigating aluminium forms and pH change. The pH in water at the beginning of the study was 4.2. The study achieved pH 5.5 using 3 t /ha of magnesian limestone.

Higgins *et al*. (2012) used pelletised lime on grassland in Northern Ireland and compared it with ground lime. Statistically-significant increases in pH were recorded in proportion to the amount of lime added up to 10 cm depth, with the largest change in the top 2.5 cm of the soil. The largest increase was from pH 5.7 to 6.1 when the application rate was 0.525 t/ha/year. However, most potato crops are grown in soil cultivated considerably deeper than 10 cm, thereby diluting the effect, perhaps by a factor of 2-3.

Pagani & Mallarino (2012) evaluated the effects of different lime sources on soil pH. From starting pH values of 5.39-5.71, maximum pH values of 7.2 were achieved using 22.4 Mg CCE / ha of calcium carbonate at three out of four sites. A follow-on study (Jones, MSc thesis, 2016) also achieved pH increases of almost 2.0 units using calcium carbonate, dolomitic lime and pelletised lime.

A review of liming in the UK was undertaken by Goulding (2016). This describes the long-term Park Grass Experiment at Rothamsted, which saw pH increase from pH 6 to pH 7 over 5 years using up to 5 t/ha of lime and from pH 5 to pH 7 using 20 t/ha.

Data from industry sources, provided by AHDB, show that it is possible to achieve pH values above 7.5. In calcareous soils, Cogman (2018) showed increases in pH above 7.5 using LimeX, with pH values as high as 8.5 being achieved in fields that had a starting pH of 7.8.

The soil's response to lime will affect how much is required to effect significant pH change. This is affected by a number of factors including the buffering capacity of the soil (higher sand content require less lime whilst soils with a higher clay content require more; Goulding, 2016); dissolution rate (limestone dissolves faster on acidic peat than sandy loam; Bailey *et al.,* 1989); soil organic matter (higher organic matter soils require more lime); cation exchange capacity; iron and aluminium levels; and soil moisture and temperature (Holland *et al*., 2018). However, in soils which require more lime following a soil test, the higher buffering capacity should result in the soil retaining lime better in the future once it has been applied. Agronomic practices also affect pH change, with more lime (and earlier application) being required on low- or no-till systems (due to lower incorporation; Alvarez *et al*., 2009). Increasing lime application and pH significantly over many years may have impacts on other crops in the rotation (see section 5).

It should be noted that organic amendments from similar sources may have different NV, e.g. poultry layer manure contains calcium carbonate, but broiler litter does not.

However, unless steps are taken to redress the balance of soils by applying a liming material there will be a natural reduction in the lime status of most soils. This results in a natural increase in acidity and in many cases a reduction in soil fertility. The main soil processes that result in acidification are the oxidation of deposited atmospheric sulphur dioxide and the breakdown of soil OM. Fertiliser use and the amount of winter rainfall will have appreciable effects on actual field losses. Losses occur as a result of:

a) leaching (the passage of water through the soil into the drainage system)
b) cropping (this loss varies with the type of crop and farming management)
c) fertilising (the use of concentrated fertilisers, particularly those with high ammonium nitrate contents accelerates lime loss)
d) pollution (the effects of acid rain)

Losses will be greatest on high pH sandy soils with high nitrogen fertiliser usage and high excess winter rainfall. Apart from initial pH and nitrogen use, the main factor affecting lime loss is soil OM, the higher soil organic the lower the lime loss. Annual lime loss from agricultural soils in the UK has been estimated at 4.25 million tonnes $CaCO_3$ which is around twice current use of liming materials (2 million tonnes in England, Scotland and Wales and *c*. 150,000 tonnes in Northern Ireland).

A significant donor to the hydrogen ion concentration in soil can be acid rain. Many nitrogen fertilisers also acidify soil over the long term because they produce nitrous and nitric acid when oxidized in the process of nitrification. Acidification also occurs when base cations such as calcium magnesium potassium and sodium are leached from the soil. This leaching increases with increasing precipitation. Acid rain accelerates the leaching of these alkali (or base) elements. Plants utilise all these alkali elements as they grow, each important to some aspect of cell tissue development and growth. Where plant material is removed, as crops are harvested, the base elements they have taken up are permanently lost from the soil, unless replaced.

3.5. Experimental evidence on lime and scab levels

As mentioned earlier, Thaxter (1892), Staes (1895), Horsfall *et al*. (1954) and Eichinger (1957) make the link between pH and calcium compounds having an effect on scab severity. More recent studies continue to highlight the complexity of the role of calcium in common scab and there are papers which do identify the application of lime as increasing common scab in some seasons.

Table **4** shows results from a trial conducted in 1989/90 by Lambert & Manzer (1991), with incidence of scab being unaffected by gypsum, but increased by the application of lime.

Table 4. Percentages of tubers in each scab severity class from soil treated with gypsum or lime

	Inoculated and harvested			Inoculated 1989 and harvested 1990			Inoculated 1989, 1990 and harvested 1990		
	Percentage of tuber surface affected								
Treatment†	0%	1-10%	> 10%	0%	1-20%	>20%	0%	1-20%	>20%
Control	80 b‡	19 a	2 a	100 b	0 a	0 a	78 b	16 a	6 a
Gypsum	82 b	16 a	2 a	100 b	0 a	0 a	78 b	17 a	6 a
Lime	47 a	41 b	12 b	68 a	18 b	14 b	20 a	35 b	45 b

†Plots were inoculated in 1989 with or without re-inoculation in 1990.
‡Means within columns followed by the same letter do not differ significantly ($P \leq 0.05$).

Wiechel and Crump (2010) found significant increases in common scab severity with the application of 5 t/ha of hot lime in the first harvest of a 3-year experiment on susceptible varieties (59 % incidence of scab versus 20 % in untreated plot). In the second year applications of 5 t/ha of hot lime and 5 t/ha of gypsum increased pH and did not elevate levels of common scab relative to the control. In the final year, overall level of scab was very high and neither 1 t/ha of hot lime nor any of the acidifying treatments had an effect on scab. The authors concluded that the effect of hot lime, dolomite and gypsum on scab development were seasonal, and suggest that factors other than pH are also important in scab symptom development. Starting pH of the soil in water was 5.2; pH values post-treatment were not published. The authors did state that differences in results between years may have been influenced by application timings, with nutrient leaching and less optimal application rates during the interval between application and tuber set when the risk of infection was greatest.

Outside of the normal sources of literature, a range of studies that explore differential applications of lime in order to change pH and the effect of these on scab levels on potato crops have been conducted. These are discussed below.

3.5.1. Experiments conducted by CUF / NIAB CUF

An experiment conducted at Cambridge University Farm designed to test the effect of soil pH on potassium availability in a clay loam soil in Hampshire was conducted by Hogge & Stalham in 1994 (Stalham, unpublished data). Builders' lime (neutralising value 70 % as CaO) was applied at two rates (0 and 8 t/ha) at planting. Initial soil pH was 6.9 and liming increased pH to 8.2. The severity of scab in the scab susceptible variety Pentland Squire was reduced from 3.5 % surface area to 1.9 % by the addition of lime. Yield was unaffected by liming.

A further experiment was undertaken by CUF on a sandy clay loam in Herefordshire (Allison, 2000a) and tested three rates of builders' lime (0, 3.5 and 7 t/ha), with a neutralising value of 73.6 %. Soil pH at planting was 5.2 and 7 t/ha lime increased soil pH at harvest from 5.3 (control) to 6.6 and exchangeable Ca from 991 mg/l to 1599 mg/l. A low incidence of scab on the very scab susceptible variety Maris Piper was found across all plots, with no lime having 2.0 % surface area affected by scab, 3.5 t/ha of lime 1.7 % and 7 t/ha of 1.4 %. The largest dose of lime had a negative effect on yield.

3.5.2. British Sugar LimeX

Lime is used by British Sugar as a purifier in the sugar extraction process and a by-product is LimeX, which may be used to correct soil pH. LimeX also contains SO_3, MgO and P_2O_5. British Sugar quotes data from the 2015 British Survey of Fertiliser Practice (DEFRA, 2016) that 23 % of the UK sugar beet area receives lime. This contrasts with only 7-8 % of arable soils receiving lime and only 1 % of potato fields receiving lime. British Sugar found anecdotal evidence that application of LimeX could reduce common scab in potatoes and undertook a series of replicated experiments in conjunction with Crop Intellect Ltd, University of Lincoln, UK to test this hypothesis (Cogman, 2018). They reviewed the recent research on the interaction of Ca with *S. scabiei* and then devised a series of replicated experiments. In 2012, they applied LimeX at three rates (3, 5, 7 t/ha) compared with a control in a field-grown crop of the variety Maris Piper. LimeX, irrespective of rate of application, reduced the incidence of tubers with common scab (29 %) compared with the control (42 %). A glasshouse experiment in 2012 also showed a reduction in scab actinomycetes on the surface of tubers where LimeX was applied (Cogman, 2018).

In 2013, four field trials were conducted with LimeX with Maris Piper on a range of soil types (Cogman, 2018). There was a reduction in the proportion of scabbed tubers on three sites as a consequence of applying LimeX, but rate (5, 7.5 or 10 t/ha) had no significant effect. Soil pH was increased on all sites, but only by 0.2-0.3 units on three fields, with the fourth increasing from 6.6 to 7.4 by applying LimeX at 7.5 t/ha. The available calcium concentration in the soil at final harvest was increased from an average of 2044 mg/l to 2317 mg/l by applying LimeX at 7.5 t/ha. Two, unreplicated strip trials in 2015 also demonstrated large reductions in the incidence of scabbed tubers, from 68-90 % infected with no LimeX to 26-37 % infected with application of LimeX at 7.5 t/ha. Cogman (2018) stated that the most effective dose of LimeX was 7.5 t/ha and that total yield was unaffected by application of LimeX. The overall increase in soil pH at final harvest by applying LimeX at 7.5 t/ha was 0.25 units (7.28 control, 7.53 LimeX). There was a gain in unscabbed yield of 6.0 t/ha across 12 trials. Cogman (2018) also reported on further work in 2016, with strips trials demonstrating no effect of LimeX in two out of the four trials, whilst the other two trials showed similar positive benefits to the 2012-2015 studies. However, the validity of these data, being based on strip trials, should be treated with caution.

3.5.3. **Gypsum**

Interestingly, whilst testing LimeX, Cogman (2018) also tested gypsum, which was found to reduce the actinomycete populations significantly compared with the control.

An experiment in 1998 on a sandy loam soil at Cambridge University Farm (Allison & Stalham 1999), found that plots treated with 160 or 475 kg/ha of gypsum ($CaSO_4.2H_2O$, equivalent to 30 and 90 kg S/ha, respectively) had a lower severity of common scab in the susceptible variety Maris Piper compared to no gypsum applied (13.9 %, 11.7 % and 21.2 % surface area affected, respectively). Applying gypsum was more effective in reducing scab severity (-8.4 % surface area) than applying the same rate of sulphur as ammonium sulphate (-4.6 % surface area). Soil pH in the top 30 cm was not affected by rate or type of product (gypsum or ammonium sulphate; mean pH 6.1). The absence of any effect of ammonium sulphate on soil pH, even at large rates is not surprising. Soil acidification will only occur when the nitrate derived from the fertiliser is leached and in so doing removes calcium from the soil. Even if all of the nitrate derived from the nitrification of 240 kg N/ha ammonium sulphate was leached, then *c.* 1200 kg/ha calcium carbonate would also be lost. In well-buffered soils, this loss would cause a decrease in soil pH of <0.5 units. Such a decrease would be difficult to measure experimentally and is unlikely to have any effect on the incidence of common scab.

A similar experiment was conducted in 1999 at CUF (Allison 2000b), on a sandy loam soil, with three rates of gypsum (500, 1000, 5000 kg/ha), calcium chloride (640 kg $CaCl_2$/ha), potassium sulphate (1050 kg K_2SO_4/ha) and potassium chloride (852 kg KCl/ha) and a control. The highest rate of gypsum reduced soil pH from 7.3 to 6.8 (but increased the quantity of extractable sulphur in the soil by a factor of 15). As the rate of gypsum increased from 0 to 5000 kg/ha, the severity of common scab in Maris Piper was reduced from 12 % surface area affected to 7 %. Interestingly, the severity of scab was reduced by $CaCl_2$, but not by KCl or K_2SO_4, suggesting that it was the calcium component of gypsum that was reducing scab, and therefore contradicting the summary of Lambert & Manzer (1991). Allison (2000b) concluded that the mode of action of gypsum on scab remained uncertain.

3.6. Suppressive soils

The concept and evaluation of suppressive versus conducive soils is still under development. Suppressive soils (in opposition to 'conducive' soils), are those in which the presence of a species or group of microorganisms acts to prevent the establishment of a pathogenic species or to restrict its growth, although the pathogen and host are both present (Schlatter *et al*., 2017). This may be despite the presence of otherwise favourable conditions, such as temperature and pH. Schlatter *et al*. (2017) cite examples of sites where successive potato monoculture has led to the development of soils that are suppressive to common scab (Menzies *et al*., 1959; Lorang *et al*., 1989; and Meng *et al*., 2012), due both to antibiotic factors and competition between pathogenic and communities of non-pathogenic *Streptomyces* species, as well as other antagonistic bacteria. These endemically occurring species effects may interact with local soil and nutrient levels to create differential effects between adjacent sites, and may change the mechanism of suppression of the scab organism (Sagova-Mareckova *et al*., 2015). Rosenzweig *et al*. (2011) used a 16S rRNA gene to establish 'operational taxonomic units' (OTUs) to characterize bacterial community richness and diversity. In total, 1,124 OTUs were detected (of which 565 were identified) in disease-conducive soil and 859 in disease-suppressive soil, including 300 found at both sites. Sequences of *Lysobacter* were found in disease suppressive soils, and *Bacillus* species were more abundant in disease conducive soils.

There is also appears to be an interactive effect between suppressive soils and variety choice (Kopecky *et al*., 2018 – unpublished preview), with scab resistant varieties seeming to promote suppressive soil-like bacterial communities.

3.7. The effect of pH on populations of microflora antagonistic to Streptomyces

pH tolerance varies widely between and within genera, and even within species strains. The suppressive function of a soil may be changed by pH, as has been seen with plant diseases such as Fusarium wilt (Scher & Baker, 1980), where a lowering of pH from 8.0 to 6.0 eliminated the suppressive effect for carnations.

Han *et al*. (2005) identified a bacterial strain which was found to be antagonistic to *S. scabiei* as *Bacillus* sp. sunhua. Antibiotic activities identified were inhibition of mycelium growth and inhibition of sporulation. Antibiotics identified as macrolactin A and iturin A were stable within a pH range of 5.0 to 13.0. Antimicrobial activity was highest at neutral pH, and was more stable in alkaline pH than acidic pH. In pot assay studies, scab infection rate reduced from 75 % to 35 % (with infection rate calculated as a percentage of infected potatoes with scab lesions over 0.5 cm in diameter).

Hiltunen *et al*. (2009) tested interactions between *S. turgidiscabies*, *S. scabiei* and *S. aureofaciens*, and non-pathogenic *Streptomyces* strains 346 and 161V (unknown species) and the commercially-available biocontrol strain K61 (*Streptomyces griseoviridis*) at different pH values in growth media. The pathogenic species grew less at pH 5.5 than 6.5 and 8.0, except *S. turgidiscabies*, which was unaffected by the three pH values tested, whereas the non-pathogenic species 346 and K61 grew equally well regardless of the pH tested. The biocontrol strain K61 showed an inhibitory effect on all of the pathogenic species at all pH values tested. Strain 346 showed a greater inhibitory effect at pH 5.5 and 6.5 than at 8.0, and a larger effect against *S. scabiei* and *S. aureofaciens*, than *S. turgidiscabies*. Growth of the *Streptomyces strain* 16IV was prevented at the lowest pH 5.5, whereas it grew well at pH 6.5 and 8.0. Strain 161V did not show inhibitory effects on pathogenic species at 6.0 or 8.0. *S. turgidiscabies* and *S. aureofaciens* also inhibited the growth of *S. scabiei* at all pH values. These results were not fully replicated in field tests and scab indices were not significantly reduced by the non-pathogenic strains, although plots with 346 and K61 did have much lower incidence of viable *S. turgidiscabies* in scab lesions than in the controls. A non-pathogenic strain *Streptomyces* 272 was effective suppressing common scab where the pH was 6.5-7.1 over a 5-year field experiment (Hiltunen *et al*., 2017.).

Arseneault *et al*. (2013) experimented with *Pseudomonas* sp. LBUM223, which has been suggested to suppress the growth of *S. scabiei* due to its production of phenazine-1-carboxylic acid (PCA). They found that it acted to reduce *S. scabiei* thaxtomin A production and hence reduced its virulence. The pH of the soil in these experiments was 6.7. Disease severity was assessed by estimating the percentage of scab lesion coverage on each harvested tuber. Scab lesions were reduced by 40-45 % in inoculated tubers. In a follow-up study (Arseneault *et al*., 2015) at pH 5.8, common scab symptoms were significantly reduced and total tuber weight increased by 46% using biweekly applications of LBUM223. LBUM223 did not reduce pathogen soil populations, nor was potato systemic defense-related gene expression significantly altered between treatments. However, a significant downregulation of txtA expression occurred in the geocaulosphere, suggesting that the *Pseudomonas* strain directly altered the transcriptional activity of the key pathogenesis gene and contributed to disease control.

Kobayashi *et al.* (2015; 2017) isolated *Streptomyces* sp. WoRs-501, which was able to suppress growth of *S. scabiei* (and *S. turgidiscabies*) in pot trials. Previous studies tested the pH range of this species in vitro (Kobayashi *et al.,* 2012) and found a range from pH 4.5 to 9.0. Lin *et al.* (2018) inhibited the growth and sporulation *of S. scabiei* with *Bacillus amyloliquefaciens* Ba01 in agar and in SSM1 medium but no pH was reported. Meng *et al*. (2013) explored the use of *Bacillus amyloliquefaciens* strain BAC03 in controlling *S. scabiei*. This strain was previously tested for pH in laboratory conditions and was found to inhibit *S. scabiei* between 3.0 and 12.0 (Meng *et al*., 2012). Beausejour *et al*. (2003) investigated the effect of *Streptomyces melanosporofaciens* on *S. scabiei*. Disease incidence was reduced in glasshouse and field experiments but no pH values were reported. Liu *et al*. (1995) report on the successful *S. diastatochromogenes* strain PonSSII and non-pathogenic *S. scabiei* strain Pon R. These were both effective in reducing scab lesions in field trials where the pH was 5.5-6.4.

In summary, the pH tolerance of microflora which may be antagonistic to *S. scabiei* varies widely between and within genera, and even within species strains. The ranges published for non-pathogenic *Streptomyces* spp. appear to be wider than for pathogenic, certainly than for *S. scabiei*. Some studies report better control by antagonists at low pH, but there were no reports of improved control at high pH.

3.8. Other antagonistic organisms

Tagawa *et al*. (2010) looked at the isolation of antagonistic fungi. They found 15 fungal strains that were differentially antagonistic to at least one of the three *Streptomyces* species *S. scabiei*, *S. turgidiscabies* and / or *S. acidiscabiei*, from nine genera (Kionochaeta, Chaetomium, Fusarium, Eupenicillium, Penicillium, Lecythophora or Coniochaeta, Cladosporium, Mortierella, Pseudogymnoascus). The suggested mode of action of growth suppression by these organisms is secretion of extracellular compounds. Most of the fungi preferentially grew in more acidic conditions and were tested against the growth of *S. turgidiscabies* at pH 5.0. Of the 15 fungal strains, 14 showed higher antagonistic activity at pH 5.0 than at pH 6.0. No testing at higher, alkaline, pH values was reported.

1.1. Summary of pH and calcium effects on scab

Whilst most pathogenic Streptomyces species have a lower pH tolerance of pH 4-5, S. scabiei has a higher upper limit than other species found in the UK (pH 7.5). Therefore, for liming policy to have a low risk in inducing scab, the pH post-liming should ideally exceed pH 7.5. The LimeX results presented by Cogman (2018) were mostly on moderate to high pH soils (6.6 to 8) where application of LimeX increased pH beyond 7.5, thereby supporting this theory. On their black fen soil where the starting pH was 5.4 and LimeX at the highest rate only increased it to pH 5.7, there was no significant effect on scab, again supporting the beyond optimum pH hypothesis. However, the work conducted by Cambridge University Farm, showed mixed results. They had one site where liming increased pH to 8.2 and there was a reduction in scab. In contrast, another site showed small reductions in scab by liming a low pH (5.2) up to only pH 6.6.

The gypsum data add supportive evidence for a non-pH induced change in scab susceptibility. Despite having a neutral or slight acidifying effect on soil pH, reductions in scab were observed by adding gypsum that could not be explained by the Ca factor since other Ca products had no effect on scab. Gypsum is a well-renowned improvement agent for low organic matter clay soils, causing clay particle flocculation, and this could have increased easily available water-holding capacity in the soil surrounding tubers. Maintenance of soil moisture levels during the period of tuber initiation has provided an effective control measure for scab, gypsum may aid this common scab control method.

3.9. Factors other than pH determining optimal growth conditions for scab

Dees & Wanner (2012) state that although common scab on potato was first described more than 100 years ago, the factors underlying the disease are still largely not understood. This is partly due to lack of understanding in terms of the pathogen itself (variation in genetics, pathogenicity, strain aggressiveness), in terms of the basis of potato cultivar resistance, and the complexity of environmental factors including: pH, soil moisture, soil microbial flora, soil organic matter (SOM), cation exchange capacity, and the availability of nutrients.

3.9.1. **Soil moisture**

Irrigation has long been used as an effective control method for scab (Lapwood *et al*., 1971; Stalham *et al*., 2015). Scab-forming species multiply on developing tubers in the first 2-4 weeks of growth after tuber initiation. Irrigation is targeted to begin after emergence to ensure that the ground is close to field capacity by TI, with particular focus on the period 1-3 weeks after TI (with varietal differences). The mechanism of control by irrigation for scab is hypothesised to be suppression of pathogen growth by wet conditions, with lower populations resulting in less disease severity (Stalham *et al*., 2014) and with a positive relationship between soil moisture and the presence of antagonistic bacteria and fungi species and an undetectable level of pathogenic *Streptomyces* in soils kept wetter than field capacity (Stalham *et al*., 2014). Gudmestad *et al*. (2008) (in Braun *et al*., 2017), suggest that water develops a protective film around the tuber, preventing infection. There may be large variations between seasons and between varieties in the reaction of common scab to irrigation (Larkin *et al*., 2012; Stalham *et al*., 2014), and between other scab species, with *S. turgidiscabies* causing common scab in high moisture soil conditions (Hiltunen *et al*., 2008).

3.9.2. **Suppressive soils**

The concept and evaluation of suppressive versus conducive soils is still under development. Suppressive soils (in opposition to 'conducive' soils), are those in which the presence of a species or group of microorganisms acts to prevent the establishment of a pathogenic species or to restrict its growth, although the pathogen and host are both present (Schlatter *et al*., 2017). This may be despite the presence of otherwise favourable conditions, such as temperature and pH. Schlatter *et al*. (2017) cite examples of sites where successive potato monoculture has led to the development of soils that are suppressive to common scab ((Menzies *et al*., 1959; Lorang *et al*., 1989; Meng *et al*., 2012), due both to antibiotic factors and competition between pathogenic and communities of non-pathogenic *Streptomyces* species, as well as other antagonistic bacteria. These endemically occurring species effects may interact with local soil and nutrient levels to create differential effects between adjacent sites, and may change the mechanism of suppression of the scab organism (Sagova-Mareckova *et al*., 2015). Rosenzweig *et al*. (2011), used 16S rRNA gene to establish 'operational taxonomic units' (OTUs) to characterize bacterial community richness and diversity. In total, 1,124 OTUs were detected (of which 565 were identified) in disease-conducive soil and 859 in disease-suppressive soil, including 300 found at both sites. Sequences of *Lysobacter* were found in disease suppressive soils, and *Bacillus* species were more abundant in disease conducive soils.

There may also be an interactive effect between suppressive soils and variety choice (Kopecky *et al*., 2018 – unpublished preview), with scab-resistant varieties seeming to promote suppressive soil-like bacterial communities.

3.9.3. **Soil factors**

The role of soil chemistry and nutrients will be discussed more below, however common scab occurs in all soil types (Dees & Wanner, 2012) and the relationship between the severity of scab and soil chemical components is complex (Lacey & Wilson, 2001; Sturz et al., 2004; Lazarovits *et al*., 2007).

3.9.4. **Temperature**

Labruyere (1971) highlighted the importance of temperature on the severity of scab symptoms, and determined in glasshouse experiments that the optimum temperature for scab isolates was 20 °C. Bouchek-Mechiche *et al*. (2000) investigated the ecology of *S. scabiei* in pot experiments and also found that it was most pathogenic at higher temperatures, either at constant 20 °C in the variety Bintje or alternating 20 / 30 °C, dark / illuminated conditions, in the variety Urgenta. Significant differences were found between *Streptomyces* species and potato varieties. *S. europaeiscabiei*, *S. stelliscabiei* and *S. scabiei* did not produce symptoms at 10 / 15 °C in either variety. In Bintje, *S. scabiei* produced the most severe common scab symptoms 20 °C and *S. europaeiscabiei* and *S.*

stelliscabiei at 20/30 °C. In Urgenta, the lowest disease severity was at 10 /15 °C and most severe symptoms were produced under the 20 / 30 °C regime in all three species.
Natsume *et al.* (2001) (in Elphinstone *et al*. (2004), found that the production of the thaxtomin phytotoxin itself varied between scab species in response to temperature change.

3.9.5. **Nutrients**

Elphinstone *et al*. (2004) built on Keinath & Loria (1989) to discuss the role of a range of macro and micro nutrients.

The effects of nitrogen are mostly indirect due to: acidification of soil by nitrogenous fertilisers (reducing levels of scab); altering the timing of tuberisation (increasing scab by causing a delay so that tubers develop when soil is drier and thus more at risk of infection); and chemical effects (suppression of *S. scabiei* due to high nitrogen or release of ammonia and nitrous acid into the soil) (Lapwood & Dyson, 1966; Keinath & Loria, 1989; Czajka *et al*., 1992; Lazarovitz *et al*., 2001 - in Elphinstone *et al*., 2004; Dees and Wanner, 2012). Different forms of nitrogen-containing nutrients may have contrasting effects on common scab; common scab may be reduced by ammonium or increased by residual nitrates (Huber, 1974; Huber & Haneklaus, 2007).

Phosphorus-containing fertilisers which increase soil pH may have an indirect effect on scab (Keinath & Loria, 1989; Elphinstone *et al*., 2004). Phosphorus deficiency may increase the severity of common scab (Rosen *et al*. (2014), however this is secondary to other factors such as pH (Rosen *et al*., 2014). Phosphorous levels may be elevated in scab tissue, but this is proposed to be an effect rather than a cause (Lambert & Manzer, 1991; Lambert *et al*., 2005; Sagova-Marekova *et al*., 2017).

Keinath & Loria (1989) found no effect of potassium in isolation, but identified the ratio of calcium to potassium as a potential factor, along with the level of exchangeable cations. Lacey & Wilson (2001) reviewed available literature, with Gries *et al* (1944) first suggesting that the ratio of calcium to potassium (Ca : K) was an important factor in scab conduciveness, and later studies which found no relationship (Doyle & MacLean, 1960; Gusenleitner, 1974; Wenzl & Reichard, 1974; Reichard & Wenzl, 1976). Lacey & Wilson's own pot trials found a slight relationship between scab and exchangeable cations (K+, Ca+ and Mg+), but this explained only 10% of the variation in scab severity. They conclude that where a high level of exchangeable cations correlated with increased scab, this was also correlated with pH, which was the main factor. Lazarovits *et al* (2007) used multivariate analysis to explore possible relationships between soil chemistry on the tuber surface and the severity of common scab. They found associations between high K % and high disease severity in some soils, and cation exchange capacity and low disease severity in another soil. They highlighted that their results indicated that some of the impact of soil chemical constituents on common scab might be soil-specific.

The use of sulphur to control scab has been researched since as early as the 19th century (Wheeler & Adams (1897) and Garman (1898), in Pavlista (2005)). The mechanism of control is unresolved; it is thought to relate to a reduction in pH (Barnes, 1972; Keinath & Loria, 1989; McCreary, 1967; Davis *et al*. 1974; Klikocka *et al*., 2006; Klikocka, 2009), although not all studies show this consistently; the application of sulphur may reduce scab without changing pH (Pavlista, 2005), and changes in pH induced by sulphur application do not always consistently reduce scab (Weichel & Crump, 2014). Sturz *et al*. (2004) examined the interaction of sulphur application with pH and bacteria antagonistic to *S. scabiei*. The study found that the application of ammonium sulphate reduced the frequency of common scab isolates in comparison to plots treated with ammonium nitrate. Results showed that bacterial communities in ammonium sulphate treated plots were more diverse. The authors hypothesise that the reduction in scab may be due to the reduction in pH providing favourable conditions for abiosis, including the synthesis of antibiotic substances in the root zone soil.
In Lambert *et al.* (2005), a review paper, scab severity was reported to be reduced with the use of sulphur (ammonium sulphate, gypsum and elemental sulphur), although results were often variable due to localised changes in pH and specificity of application time required (i.e. before tuber set).

Manganese availability increases as pH reduces and soil moisture rises, and some studies have found beneficial effects of manganese against scab (McGregor & Wilson, 1966; Grzeskiewicz *et al*., 1990; Keinath & Loria, 1989; Saha *et al*., 1997, in Elphinstone *et al*., 2004). However, other experiments have found no effect (Keinath & Loria, 1989; and Gilmour *et al*., 1968 in Elphinstone *et al*., 2004) or phytotoxic effects (Barnes, 1972 in Lambert *et al*., 2005). Lambert *et al.* (2005) discuss the theory that high Mn at low pH is part of a mechanism for suppression of *S. scabiei* as Mn is toxic to it, but argue that Mn would be below a toxicity threshold and maybe acting to improve host resistance to pathogens possibly via its function as an enzyme co-factor or oxidation of phenolics.

Variable effects have been found in the effect of boron and boric acid application, as reviewed by Keinath & Loria (1989), including increases, decreases and unchanged levels of scab.

Copper, a biocide, does control potato scab, but commercial use is limited by negative effects on plants and yield (Elphinstone *et al*., 2004).

Zinc and iron were not considered to have any effect on scab, although Elphinstone *et al*. (2004) suggest further work is necessary of the possible physiological effects of iron. Brazda (1995) (in

Klikocka *et al*., 2005) suggest that an insufficient supply of nutrients (including manganese, potassium, magnesium, zinc and boron) may favour scab infection. El-Sheikh *et al*. (2010) found a negative correlation between zinc soil concentration and scab severity. Zinc is released into the soil at lower pH values (Wale, 2000). Experimental control of other pathogens (such as powdery scab, Braithwaite *et al*., 1994) with zinc sulphate were successful but had phytotoxic effects.

3.9.6. **Variety**

Potato cultivars vary in their resistance to common scab and the basis of resistance is not fully understood (Dees & Wanner, 2012). From a biochemical viewpoint, Acuna *et al*. (2001) investigated cultivars with varying degrees of resistance to scab *in vitro*, and suggest that in resistant varieties, tubers metabolise the thaxtomin toxin produced by *S. scabiei* (through glucosylation) and are able thereby to detoxify it. Kristufek *et al*. (2015) posit that the effect of cultivar on scab severity may be related to the increased presence of calcium in scabby periderm tissue and other healthy parts of the plant. They argue that the increase in calcium is a stress-response induced by thaxtomin and that varietal differences occur because cultivars differ in their ability to uptake calcium and regulate water under stress in the presence of the pathogen.
Tuber constituents are understood to play a role (Rich, 1983; Abo Elyousr *et al*., 2016), and studies have covered nutrients including calcium, potassium and manganese (Davis *et al*., 1976), reducing sugars (Goto, 1981) and the phenolic acid content of tuber peel (Singhai *et al*., 2010). Varietal resistance may be variable and may interact with other factors mentioned above, including soil nutrients and minerals, as well as physiology and pathogen strain (Klikocka *et al*., 2009; Wanner & Haynes, 2009; Dees & Wanner, 2012; Stalham *et al*., 2015; Abo Elyousr *et al*., 2016).

4. Soil properties

The changes caused by lime application in the soil are complex and may be physical, chemical and biological.

4.1. Physical effects

A satisfactory granular crumb structure is encouraged in an acid soil by the addition of any form of lime, although the influence is largely indirect. For example, the effects of lime upon biotic forces are significant, especially those concerned with the decomposition of the soil OM and the synthesis of humus. The generation of humus as well as its persistence greatly encourages granulation of soil aggregates.

Chambers (1985) showed that the addition of lime produced increases in aggregate stability (i.e. decreases in dispersible clay) and the plastic limit, decreases in linear shrinkage and denser cracking patterns. This suggests that, in the field, limed soils will show a tendency to form smaller aggregates that are themselves structurally stable, showing limited swelling and shrinkage, and are unlikely to be dispersed upon wetting. Chambers stated that the explanation of these lime-induced changes in soil physical properties was difficult to ascertain, because of the many complex interactions occurring upon lime addition. The orientating effect and metastable configuration provided by the Ca ion, and the ability of Ca to act as a cation bridge between clay and OM, plus the additional newly activated exchange sites produced upon liming, may all have a significant effect in stabilizing the system. Additionally, liming promotes the production of organic polymers which may impart stability to the aggregates. A full explanation of the respective parts played by lime and OM has yet to be discovered; however, the answer probably lies in the clay-Ca-OM interactions, and the increased rates of OM turnover upon lime addition.

Grant *et al*. (1992) discussed the effect of incorporating calcium into structurally-degraded soils. It can increase 'fracture surface roughness' (and soil friability – improving workability; Shanmuganathan & Oades, 1982), reduce the mechanical strength (Aylmore & Sills, 1982) and reduce dispersion and crusting (Davidson & Quirk, 1961; Bakker *et al*., 1973). The aim of the study was to investigate the extent to which previous additions of calcium to a structurally-degraded soil have residual effects of the fracture surface roughness and soil strength. Gypsum and calcium carbonate were added in 1980, with soil samples taken in 1986/7 from treatments of 0, 2 (1986 only) 4, 10, 14 and 20 t/ha. Applications were worked into the top 150 mm of soil, and no tillage occurred after 1980. Because most of the calcium had leached out of the soil by the time measurements were taken, only effects on microstructure gave significant results. In 1986 the amount of calcium applied had no effect on soil water or carbon content. Fracture surface roughness values were lower as calcium increased. There was an increase in the number of pores greater than 30 µm; increased water content in these pores gave increased tensile strength and penetrometer resistance in soil clods and partly concealed the effects of calcium on fracture surface roughness. The effects of lime would not normally be detectable 6-7 years after application; however they were preserved due to the lack of tillage and irrigation.

4.2. Chemical effects

The questions posed for this section on soil chemistry were:

- What is the effect of the clay content of the soil, the timing of Ca application and neutralising value (product and grade, e.g. Chambers 1985) on soil pH?
- Do low reactivity products need to be timed differently to high activity since it is recommended that they be applied 12-18 months ahead of a sensitive crop?
- Does changing pH alter nutrient availability?
- Do large applications of K fertiliser increase the loss of soil Ca?

Maintaining optimum soil pH values in all parts of the field is essential in order to maintain soil quality and health, crop quality and yield. For each field, the amount of lime to apply will depend on the current soil pH, texture, organic matter and the target pH, which should be 0.2 pH units above optimum. Clay and organic (>10 % OM) soils need more lime than sandy soils to increase pH by one unit. A lime recommendation is usually for a 20 cm depth of cultivated soil (AHDB, 2017). Table **5** provides examples of the recommended amounts of lime required to raise the pH of different soil types to achieve the target pH level shown in the footnotes. Where soil is acid below 20 cm and soils are ploughed for arable crops, a proportionately larger quantity of lime should be applied. However, if more than 10 t/ha is needed, half should be deeply cultivated into the soil and ploughed down, with the remainder applied to the surface and worked in.

A liming material should always be well worked into the cultivated soil because it can take several months to increase pH throughout the topsoil. If it is important to try to achieve a rapid effect, then use of a fast-acting product (e.g. burnt or slaked lime) should be considered.

Table 5: Lime recommendations in terms of tonnes of lime (NV50) to apply per hectare (AHDB, 2017b, p14)

Initial soil pH	Sands and loamy sands		Sandy loams and silt loams		Clay loams and clays		Organic soils[a]		Peaty soils[b]	
	Arable	Grass	Arable	Grass	Arable	Grass	Arable	Grass	Arable	Grass
	Liming factor									
	6	4	7	5	8	6	8	6	16	12
	t/ha									
6.2	3	0	4	0	4	0	4	0	0	0
6.2	4	0	5	0	6	0	6	0	0	0
5.5	7	3	8	4	10	4	10	4	8	0
5	10	5	12	6	14	7	14	7	16	6

[a] For mineral and organic soils, the target soil pH is 6.7 for continuous arable cropping and 6.2 for grass. Aim for 0.2 units above the optimum pH.

[b] For peaty soils, the target soil pH is 6.0 for continuous arable cropping and 5.5 for grass. Aim for 0.2 units above the optimum pH.

There are broad differences between soils in England and Wales and Scottish soils. For example, Scottish soils often have naturally lower pH levels than those in England and they often contain higher OM levels. For these and other reasons, soil testing methods and recommendations for use of lime and fertilisers have been developed separately for the Nutrient Management Guide (RB209) for use in England and Wales from those in Scotland (SRUC, Technical Note 656).

Recommended target soil pH values for England, Wales and Northern Ireland and for Scotland are shown in Table **6** for arable and grassland on mineral and peaty soils. Different laboratories use different solutions when testing soil pH and care must be taken when interpreting the results. In England and Wales, water is used. The (Scottish) SRUC soil testing lab uses calcium chloride solution (0.01 M $CaCl_2$), but adds 0.6 to their results so that they can be compared with the results of tests done using water. Some other labs are now using calcium chloride solution too, but do not add 0.6 to their results before sending them out to farmers. It is important to clarify whether water or calcium chloride solution has been used and whether 0.6 is being added to the results where calcium chloride solution has been used. Only if this is known can soil pH values be compared with target values and past results so that appropriate management decisions can be made for the soil in question.

Table 6. Target values for soils in England, Wales and Northern Ireland and for Scotland.

	Optimum soil pH			
	England, Wales, Northern Ireland		Scotland	
	Mineral soils	Peaty soils	Mineral soils	Peaty soils
Continuous arable cropping	6.5	5.8	6.0 – 6.2	5.7 – 5.9
Continuous grassland	6.0	5.3	6.0	5.3 – 5.5

In arable rotations, growing acid-sensitive crops such as sugar beet, maintaining soil pH at 6.5 - 7.0 is justified

Although the recommendations and the way in which they are presented differs somewhat between England/Wales and Scotland, the principles are very similar. For each field, the amount of lime to apply will depend on the soil pH, soil texture, soil organic matter content and the target pH. Clay and organic soils require more lime than sandy soils to increase the soil pH by one unit, but sandy soils will generally require more frequent liming. Lime recommendations are usually for a 20 cm depth of cultivated soil or for a 7.5 cm depth of grassland soil. Where soil is acid below 20 cm and soils are ploughed for arable crops, a larger dressing of lime should be applied.

The optimum pH for arable crops grown on mineral soils in England and Wales as reported by MAFF (1981a), pH 6.5 (water), represents the so-called 'target pH' we aim to achieve when liming. The Macaulay Institute for Soil Research (1984) report an optimum pH of 6.2 for arable crops grown on mineral soils in the north east of Scotland. The James Hutton Institute and SRUC in standard advisory work determine soil pH in 0.01M $CaCl_2$, the target pH when liming being pH 5.6 (0.01M $CaCl_2$), i.e. 0.6 units lower than the water pH.

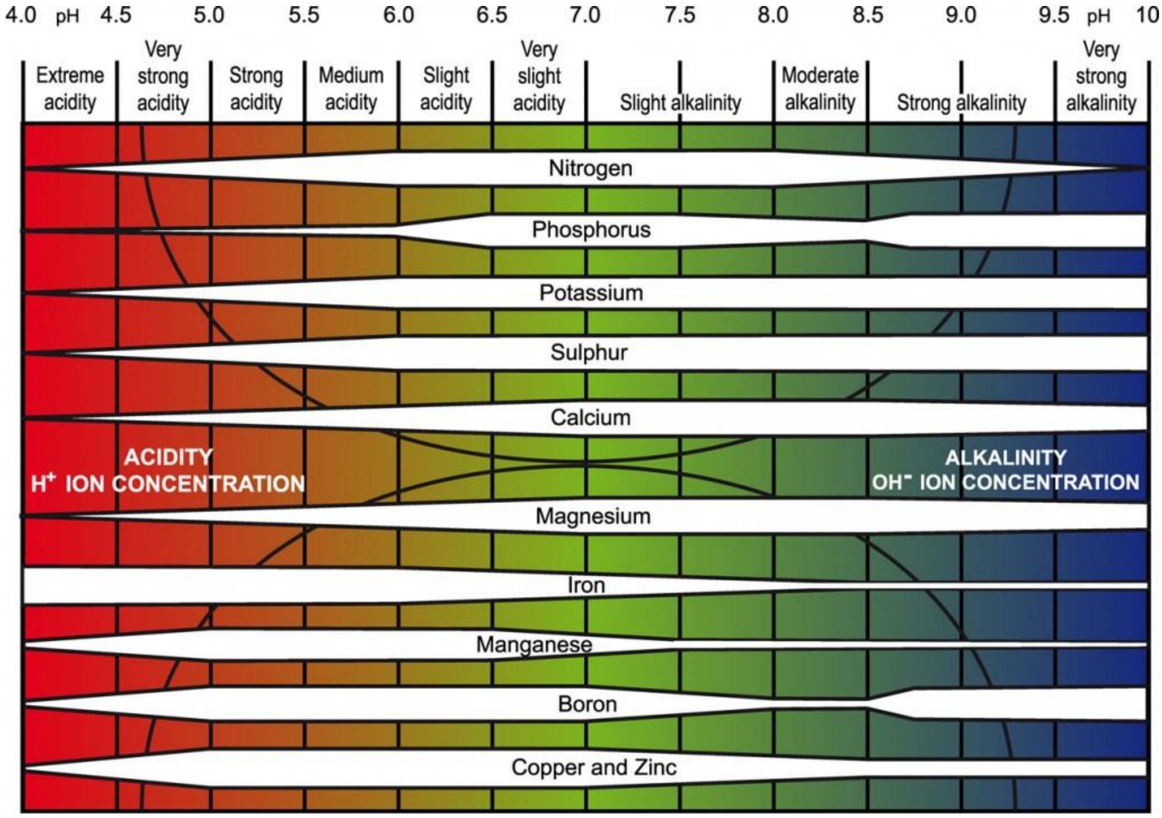
If an acid soil (e.g. pH 5) is limed to a more suitable pH value of 6.5-6.7, a number of significant changes occur (Brady, 1974):

1. The concentration of hydrogen ions will decrease.
2. The concentration of hydroxyl ions will increase.
3. The solubility of Fe, Al and Mn will decrease.
4. The availability of P and Mb will increase.
5. The exchangeable Ca and Mg will increase.
6. The percentage base saturation will increase.
7. The availability of K may be increased or decreased depending on conditions.

The optimum availability of most plant nutrients occurs over a narrow range of pH, typically 6.5 in continuous arable cropping on mineral soils and 5.8 in peaty soils (Figure **2**). At high pH (> 7.5), Fe, Mn, B, Cu and Zn are less available than at the optimal pH 6.5.

As crops remove dissolved K from the soil, it is replaced from the soil, and this in turn is replaced on the soil by another cation. As the concentration of other cations such as Ca and Mg increases, the absorption of K by the soil decreases. Therefore, the addition of lime or gypsum will increase the supply of Ca which may reduce the availability of K.

Figure 2 The availability of different nutrients at the different pH bands. The wider the white bar, the more available is the nutrient (redrawn for the Potash Development Association from Truog, 1946).



Some UK farmers and growers are now testing their soils for base cation saturation ratios, which places emphasis on the importance of the ratio between the quantities of certain cations present including Ca and Mg. A common question is whether there is a detrimental effect from adding extra Mg (in the form of magnesian limestone) where soil pH is below target, but where the soil Mg is above the target of Index 2 (moderate in Scotland). Calcium can improve the structure of heavy soils by causing the soil particles to move apart, thus improving aeration and drainage, whereas magnesium makes the soil particles aggregate. The ratio between the concentrations of these two cations therefore may have an impact on soil structure (Eric Anderson, personal communication). As a general rule, if your soil has a Mg index of 3 (high in Scotland) then it would be wise to consider applying a liming agent which contains little or no Mg rather than choosing magnesian limestone. This may also help to avoid potash (K) deficiencies which can be brought on by an excessively high Mg:K ratio.

A considerable amount of research has been done worldwide aimed at interpreting the role of cation ratios on soil structure. However, very little of it clearly demonstrates the benefit of having a particular ratio of Ca:Mg. It would be quite possible to achieve the “chosen ratio” between them, yet have a soil which contained either very low or very high levels of both. Although there is no definitive ratio, a ratio of extractable Ca:Mg in clay soils of between 4:1 and 7:1 is expected to ensure that Mg is not excessive and likely to be detrimental to soil structure and aeration (Eric Anderson, personal communication).

4.3. Biological effects

Lime stimulates the general purpose, heterotrophic soil organisms (Brady, 1974). This stimulation not only favours the formation of humus, but also encourages the elimination of certain organic intermediate products that might be toxic to higher plants. Most of the favourable organisms, as well as some of the unfavourable ones such as those that produce potato scab (Brady, 1974), are encouraged by liming. The formation of nitrates and sulphates in soil is markedly increased by raising the pH, and this might be very important in close proximity to roots rather than in the overall soil bulk. The bacteria that fix nitrogen from the air, both non-symbiotically and in the nodules of leguminous plants, are especially stimulated by the application of lime. The successful growth of most soil microorganisms is so dependent upon calcium, that satisfactory biological activities cannot be expected if Ca or Mg levels are low and liming is a crucial activity to maintaining calcium levels.

4.4. Other effects of liming on soils

This is not a full review on the physical effects of the use of lime on soils. Key references including reviews on this subject include Holland *et al*. (2018), Goulding (2016) and Paradelo *et al*. (2015). Some impacts of lime on soil structure were discussed earlier. Paradelo *et al.* (2015) report on overall trends in soil structure as affected by liming, whilst other studies, including Foornara *et al.* (2011) and Grant *et al.* (1992), suggested that liming improves soil structure due to the presence of calcium encouraging carbon to be stored as humus rather than labile carbon. Chan & Heenan (1999) and Manna *et al.* (2007) both report improved soil structure in limed soils. Kaiser *et al.* 2014 found no effect of liming on the formation of silt-sized aggregates and Fernández-Ugalde *et al*. (2011) suggest that liming may imply a change in the nature and relative importance of the bonding agents responsible for the stability of macroaggregates. Paradelo *et al*. (2015) summarised the effects of lime upon the soil as reducing aluminium saturation or increasing pH to increase nutrient availability, increased soil biological activity (which favours the mineralization of organic matter and results in CO_2 losses and a decrease of the soil organic carbon (SOC) stocks); amelioration of soil structure, increasing the stability of clay assemblages and clay-organic matter bonds, which should bring an increase in SOC physical and physicochemical protection; and increasing plant productivity (due to improved soil conditions) and the return of C inputs to soil (potentially increasing SOC concentrations). Paradelo *et al*. (2015) highlight that the net effect of these processes is not well understood yet, although increases in productivity seem to be higher than losses due to mineralisation. Other positive actions include the cementing actions of carbonates, and the altered exchangeable cations may also improve the adsorption of organic matter. However, increasing greenhouse gas by increasing soil pH could be a negative relationship. The Intergovernmental Panel on Climate Change is as sobering as it is scary. According to the study, the world is still on track to overshoot its target, set out in the 2015 Paris Agreement, of holding global temperature increases to well below 2 °C. Despite many years of trying to contain greenhouse gas (GHG) emissions and so slow global warming, the problem seems to be getting worse. Globally, emissions from agriculture amount to 15% of all GHG emissions, and even in the UK, the figure is about 10%.

4.5. Lime application determination and method

Recommendations for target pH and lime applications (Table 5) are in RB209 and lime requirement (LR) calculators are available, such as RothLime (Goulding, *et al*., 1989). Chambers (1985) found that the variables pH, pH-dependent CEC', NHitOAc-extractable Al and KCl/LaCl3- exchangeable Al were shown to be highly correlated with LR. His most successful regression equation for predicting the $CaCO_3$-LR 5.8 incorporated the terms (5.8-pH) + $LaCl_3$-exchangeable Al + (5.8-pH) x OM + CEC 5.8 (R^2= 98.8%). The important contribution of organic matter (OM) to the pH-dependent CEC (r = 0.712***) was shown and, on a weight basis, OM was found to contribute four times more than clay to the pH-dependent component. However, clay content was shown to make an important contribution to the overall 'effective' CEC (r = 0.645***). Accompanying the lime-induced increases in CEC there were decreases in exchangeable Mg and K and solution Mg, the result of these being retained more strongly and in greater quantities against displacement by 0.1M BaCl2-

The following paragraphs involving studies examine in more detail the potential results on pH of split-dosing and reactivity and rate of dissolution (which is determined by particle size and hardness). The neutralising value (NV) of a liming material is expressed in terms of the percentage of calcium oxide equivalent. Thus, 100 kg of a liming material with an NV of 52 % will have the same neutralising value as 52 kg of pure calcium oxide (CaO). Neutralising value is determined in the laboratory and is calculated from the results of the chemical reaction with known strength hydrochloric acid, and always refers to the sample 'as received' rather than on a dry matter basis.

The effectiveness and speed of reaction of a liming material can be quantified in the laboratory using the "Reactivity Test". The results obtained from this test may be used to estimate the behaviour of a liming material in the soil. These results bear a good correlation with results obtained from long term pot trials. The Reactivity Test involves the decomposition of the liming material in hydrochloric acid under stable pH conditions. The acid consumption during a given time is a direct criterion for the reaction time of the liming material being tested. The results of the test are expressed as a percentage, and they compare the speed and effectiveness of the sample with pure precipitated calcium carbonate.

For maximum effectiveness, the harder and less porous the parent rock, the finer the liming material must be ground. An indication of the importance of the fineness of grinding can be seen from ADAS field trial results carried out over a number of years (https://aglime.org.uk/tech/lime_effectiveness.php). In the short term, the effect of the finer liming materials was even more marked. Where lime is applied to an acid soil, there is a well proven relationship between the fineness of grinding, pH change and the crop yield response. There is a considerable reduction in the effectiveness of liming materials containing particles above 600 microns (0.60mm, 60 mesh) unless the material is easily broken down. Consequently, fineness is slightly less important in respect of:

- Burnt lime which breaks down to a fine powder as a result of chemical reaction with water.
- Soft, porous chalks which break down easily in the soil from the action of frost or the passage of cultivating implements.

An experiment to investigate aluminium forms and pH change in high aluminium acidic soils in Galicia, Spain, was conducted by Alvarez *et al*. (2009). A dose of 3 t/ha of magnesium limestone was applied to plots, with a neutralising value (NV) of 87.8 % and 25.4 % calcium. The pH in water at the beginning of the study was 4.23. The study found greatest change in pH where a finer magnesium limestone was applied (<0.25mm diameter grain) (up to around pH 5.5), and that a greater pH change was achieved if the application was not split.

Higgins *et al*. (2012) compared the performance of pelletised lime with ground lime in grassland in Northern Ireland. The mean starting pH of the site was 5.8. Four rates of pelletized (dolomitic) lime were applied annually: 0, 175, 350 and 525 kg lime/ha/year, with the same rates of ground (dolomitic) lime as a comparison. Both products had an NV of 55 %. No differences were found between the pelletised and ground lime for any of the variables measured (including grass yield, pH, exchangeable cations, magnesium or phosphorus). In addition to the lime, five rates of calcium ammonium nitrate (CAN) fertiliser – 0, 75, 150, 225 and 300 kg N/ha/year – were applied, split over three applications and with each rate of lime combined with each rate of CAN to examine any interactions. Statistically significant increases in pH were recorded with the largest increase in the top 2.5 cm of the soil, in proportion to the amount of lime added, up to 10cm depth. The largest increase was in the 525 kg/ha/year (0.53 tonnes/ha) application rate, pH increased from 5.7 to 6.1. Control plots receiving no lime showed non-statistically significant decrease in pH over the three years. There was no difference in speed or performance of pelletised lime. Higgins *et al*. (2012) recommend that pelletised lime would only be applied annually to maintain a higher pH once an increase has been achieved using a single large application of ground lime, largely due to cost the pelletised lime.

An experiment designed to evaluate the effects of different lime sources on soil pH was conducted using pure calcium carbonate, calcitic limestone, and dolomitic limestone at 0, 4.5, 9, 13.5 and 22.4 Mg/ha calcium carbonate equivalent (CCE) (Pagani & Mallarino, 2012). The maximum pH achieved was always higher (and faster) with calcium carbonate than with dolomitic limestone, and sometimes higher than calcitic limestone. This was explained as being due to the particle size being finer. From starting pH values of 5.39-5.71, maximum pH values of 7.2 were achieved using 22.4 Mg CCE / ha of calcium carbonate at three out of four sites. A follow on study (Jones, MSc thesis, 2016) also achieved pH increases of almost 2.0 units using calcium carbonate, dolomitic lime and pelletised lime. Again calcium carbonate reached the highest maximum pH (and fastest). The means across soils for calcitic and dolomitic limes shows the two finest fractions increased pH for the longest duration.

A 30-year experiment in Latvia designed to remediate acidification of soil from fertiliser application using lime was reported by Vigovskis *et al*. (2016). Four rates of lime were applied using shale ash (NV 80 %; 415.4 g/kg CaO) at 0, 2.58 t/ha, 5.70 t/ha and 11.4 t/ha. Primary liming was done in 1981 with maintenance liming with dolomitic limestone (97.0 % NV) in 1994 and with BALTKALK with 97.6 % NV in 2004. The crops were in a 7-year rotation with potato in the second year. After the first application in 1981, soil pH increased from 4.8 to 5.8-6.0. After the first maintenance application in 1994, this increase in pH was broadly achieved again. Over the next 20 years (to 2004), soil acidity increased due to NPK fertiliser applications; pH reduced to 5.6 in plots treated at the 11.4 t/ha rate, and 4.6 in those treated at 2.58 t/ha. Un-limed plots had final pH values between 4.4 and 4.8. The study did not mention potato scab, but did mention that potato yield was impacted by differential fertiliser rates, and not by liming rates, which had no significant effect on yield.

5. Rotational effects

The liming of acidic soils has been found to improve the yields of most crops in the UK (Holland *et al*., 2018), but the relationship between yield and soil pH differs between crops and is influenced by soil type and texture (citing Liu *et al*., 2004; Farhoodi & Coventry, 2008; Fageria, 2009; Fageria *et al*., 2011; and Goulding, 2016). Holland *et al*. (2018) used data from long-term liming experiments at Rothamsted Research to explore the relationship between crop yield and pH. Although fewer data were available than for other crops, the trend suggested that potato crops in the UK generally achieved maximal yields at a lower soil pH than other crops such as wheat, beans or oilseed rape, although the magnitude of this difference depended on field site (Holland *et al*., 2018). Minimum pH values below which crop growth may be restricted on mineral soils were cited in Goulding (2016), taken from MAFF advice (1981). Field beans (*Vicia faba*) are the most susceptible to soil acidity requiring a pH of at least 6.0; barley and sugar beet require pH of at least 5.9; wheat (*Triticum aestivum*) requires a pH greater than 5.5, whilst potato has the lowest tolerance of pH of 4.9 (Goulding, 2016).

Yield benefits at higher pH values can be through the better acquisition of both water and nutrients, due to the increased availability of nutrients by soils at a higher pH and the development of improved root systems associated with liming (Holland *et al*., 2018).

NRM Laboratories Ltd offer expert analytical services for agriculture, horticulture, amenity and environmental services within the land based industries and have compiled a large dataset on soil nutrient status. NRM were contacted as part of the review and kindly agreed to send anonymised historic data on soil pH collected from 2014-2018. Overall, there were >112,000 samples from soils growing arable, grassland and vegetable and bulb crops. The summary of these data is presented in Table **7** and shows that pH is being maintained close to neutral in most soils. When examining samples where the next crop was specified as potatoes, the mean and upper and lower 10 percentiles were identical to the overall data, indicating that this crop is not being maintained at lower soil pH than the average for arable land. However, where potatoes were grown immediately prior to sampling, soil pH was significantly lower than the value for land destined for potatoes in the following year (Table 7). It is not certain why there should be this discrepancy between post- and pre-potatoes, but one reason could be that growers only apply lime post potatoes in their rotations.

Table 7. Summary of soil pH as recorded by NRM Laboratories Ltd from 2014-2018

Crop	No. samples	Mean pH	Upper 10 percentile pH	Lower 10 percentile pH
All arable, grass, vegetables, bulbs	112529	6.91	8.04	5.82
Potatoes as next crop	12689	6.85	8.02	5.71
Potatoes as previous crop	2509	6.56	7.84	5.56

Additionally, a total of 42 surveys from the ongoing NIAB-CUF managed AHDB Rotations Project were accessed to explore current liming practices. There were 10 fields that were limed that had potatoes in the rotations. Of these, three growers limed immediately before sugar beet and all were around 1-2 years before potatoes were grown. Only one field was limed immediately before potatoes.

5.1. Long-term studies of liming across the rotation

In a long-term experiment (1991-2001) aimed at determining the effects of conventional tillage versus no-till, and liming versus no liming, on nitrogen cycling in Alberta, Canada, Soon & Arshad (2005) applied lime at rates of 0 and 7.5 t/ha. In 1991, the starting pH was 5.1. In 1995, pH in limed plots had increased to 6.0, compared to 5.0 in the control. In 2001 soil pH was 6.0 in limed plots versus 5.3 in the control. A significant tillage x liming interaction was found, with increased carbon and nitrogen cycling and crop growth of barley (*Hordeum vulgare*) and canola (*Brassica rapa*) in plots with no-till and lime. This was presumed to be due to the positive impact of lime and no-till on micro-organisms.

Vigovskis *et al*. (2016) undertook a 34-year experiment in Latvia to examine the relationship between yield and acidity of a range of crops (including potato, cereals and oilseed rape) using lime and fertiliser applications in a 7-year rotation. Slate ash lime was initially applied in 1981, with maintenance liming in 1994 and 2014. Potatoes were grown in 1995, 2002 and 2009, meaning lime was applied in the previous year to the 1995 crop. After the first application of lime, soil pH increased from pH 4.8 to pH 5.8-6.0. Between 1981 and 1994, soil pH decreased by 0.4-0.6 pH units (compared to 0.7-0.8 in the control). After the first maintenance liming, the soil pH returned almost to the starting level. Between 1994 and 2004, in the treatments with highest liming rate (11.4 t/ha $CaCO_3$) the pH decreased to 5.2. In the treatments with the lowest liming rate (2.6 t/ha $CaCO_3$), the pH decreased to 4.6 (compared to 4.4 in the control). The results showed that long-term fertilization and periodical liming positively affected the productivity of crops compared to control plots. Yield figures were not provided for all years, but results for the 2009 potato crop suggest that fertiliser application had a greater effect than liming, and that liming at 5.70 t/ha gave the largest yield in all fertiliser treatments.

Woodard & Bly (2008) measured soil pH change and maize and soybean responses over eight years comparing 2.0 Mg/ha applied annually with 8.0 Mg/ha applied once every four years. Mean grain yields for both maize and soybean increased for all lime treatments compared to the control.

5.2. The impact of liming on other crops

5.2.1. Current recommendations

Liming has consequences for other crops in the rotation, particularly on diseases and nutrient availability. These are discussed by crop with consideration of the timing and application method of lime advised.

The optimum pH for each cropping system and soil type is based on the overlap between the optimum availability of plant nutrients in soil (AHDB, 2017b). The Nutrient Management Guide (RB209) states that the optimum pH for continuous arable cropping is 6.5 in mineral soils and 5.8 in peaty soils (± 0.5) (AHDB, 2017b). In arable rotations which include acid-sensitive crops such as sugar beet and barley, applying lime before these crops are grown and maintaining soil pH between 6.5 and 7.0 is justified. Target values for vegetable rotations are soil pH 6.5, or 7.0 for Brassicas if clubroot is a problem (pH 5.8 on peat soils). RB209 Section 5 recommends a lower pH optima than this for potatoes. As covered previously, liming immediately before potatoes is currently not recommended to avoid increased risk of scab (AHDB, 2017a). Teagasc in Ireland recommends that it is a good practice to lime the soil after harvesting potatoes. Where a good rotation is followed, at least five years will have elapsed before the next potato crop (TEAGASC, 2018).

Acidic soils tend to be more conducive to diseases caused by fungi, with increasing pH tending to ameliorate symptoms; whereas less benefit from liming is seen in bacterial and viral pathogen related diseases (Holland *et al*., 2018). Improvements in fungal disease management with the increase in pH may be due to the pH range of the pathogen, increased growth of antagonist species, the release of nutrients for plant metabolic processes or the host plant susceptibility to the disease (Holland *et al*., 2018).

In terms of nutrients, molybdenum, manganese, boron and zinc are identified by RB209 as being impacted by liming (AHDB, 2017c and AHDB, 2017d). Liming can help to reduce molybdenum deficiencies in oilseed rape, cereals and vegetables to raise the soil pH of acidic soils to 6.5. However, RB209 cautions against high pH and over-liming in oilseed rape, cereals and vegetables to avoid the risk of manganese deficiency in any soil with pH above 7.5; sandy soils with pH above 6.5; organic, peaty or marshland soil with pH above 6.0.

High pH and over-liming also increase the risk of boron deficiency in oilseed rape and vegetables. All soils above pH 7.5 are at risk. Sandy soils with a pH above 6.5 and organic, peaty or marshland soils above pH 6 are at a greater risk. Carrots are particularly mentioned; boron deficiency can affect carrots on light textured soils with a pH >6.5, particularly in dry seasons. Zinc deficiency is rare in the UK, however for cereals and vegetables, sandy soils with high pH and high phosphate status are more likely to have lower levels of zinc.

5.2.2. **pH and boron sensitivity in sugar beet**

Lime is required to correct soil pH to maximise yield and sugar content of sugar beet (BBRO, 2018). Mild yield effects can be seen on mineral soils with pH below 6.5 with more serious effects of soil acidity occurring on soils with pH below 6.0. BBRO recommends that lime products be applied 12-18 months before pH sensitive crops to ensure thorough incorporation of the liming product with the soil. However, finer, more reactive products such as LimeX or ground chalk and limestone products with >40 % passing 0.15mm can be applied successfully in the autumn before cropping with sugar beet (BBRO, 2018). Sugar beet has a high boron requirement, which becomes less available at high pH values and high calcium carbonate levels (Niaz *et al*., 2007; Dridi *et al*., 2018). Boron deficiency leads to severe leaf symptoms and ultimately reduced yield and sugar content.

5.2.3. **Clubroot in brassicas**

Brassicas may suffer from infection by the clubroot pathogen, *Plasmodiophora brassicae*. Root galls affect root function, reducing uptake of water and nutrients. Clubroot severity is linked to soil pH and boron and calcium content, and crops in acidic soils are more at risk of severe symptom development (Donald & Porter, 2009; AHDB, 2015; Holland *et al*., 2018). Although the clubroot pathogen is highly resilient and will survive and infect at high soil pH levels, soil amendments that raise the pH and calcium content of soils can be effective. A spike in pH and available calcium at drilling has been shown to reduce clubroot infection. A neutral or alkaline pH (≥7) will be most effective in reducing clubroot in oilseed rape and vegetable crops (AHDB, 2015). The guidance does consider that raising pH over 6.5 for following cereal and potato crops may impact nutrient deficiencies (AHDB, 2015).

Field trials in an AHDB Cereals & Oilseeds-funded project (Project Report 487) (Burnett *et al*., 2013) where LimeX70 (calcium carbonate) was applied just before drilling winter oilseed rape at 8 t/ha gave average control of clubroot of 25 % over the trial series with modest yield benefits. However, control was variable, ranging from no significant effect to 90 % control at different sites. The reason for this variability was not clear, but poor control was noted at very severely infested sites and oilseed rape should not be grown where clubroot levels are very high (AHDB, 2015). Finely ground forms of lime have been shown to be more effective than coarser forms. Yield benefits were sometimes cost effective in the trial series, but the advice is that even where there is no immediate cost benefit, liming should be considered as part of a long-term strategy for reducing clubroot build-up in affected fields (AHDB, 2015).

Other published field trials have reported inconsistent results with the control of clubroot through the application of lime (Chinese cabbage - Knox *et al*., 2015; oilseed rape - McGrann *et al*., 2016). Control varied across sites and years, from no significant effect to 95 %. This suggests that the interaction of variety, nutrients, pH and inoculum load on clubroot development and expression can be greater than the changes induced by liming (Knox *et al*., 2015; McGrann *et al*., 2016; Holland *et al*., 2018).

5.2.4. **Cavity spot disease in carrots**

Cavity spot disease in carrot is caused by members of the genus Pythium (*P. violae* and *P. sulcatum* in the UK (Hiltunen & White, 2002)). Experiments have suggested that lime may be used to raise the pH of soils, and reduce incidence (El-Tarabily *et al*., 1997). The role of calcium is also not understood (Hiltunen & White, 2002). A role for calcium, using lime and gypsum, has been specifically tested in glasshouse experiments and was not supported (El-Tarabily *et al*., 1997). The method of suppression of cavity spot by pH and lime is not understood, and highly contrasting results are found between sites and between years (Hiltunen & White, 2002; Gladders *et al*., 2014).

The treatment of soils with lime one month before drilling was found to be more effective than its application at drilling and in a control (Hiltunen *et al*., 2000; Hiltunen & White, 2002).

Experiments undertaken as part of the AHDB Project FV391 (Carrots: Improving management and control of cavity spot, Gladders *et al*., 2014), LimeX (which added calcium and significantly increased pH) was found to reduce the incidence of cavity spot in one of two testing sites. Site and year was found to be a more important disease determinant than LimeX application. No difference in cavity spot was found between one application of lime before drilling and two prior to drilling.

The most recent published advice on cavity spot from AHDB (HDC) was 2013, advised that fungicides should be the main method of control for cavity spot, with more research needed on lime (and LimeX) (AHDB, 2013).

6. Economics

6.1. The effect of liming on tuber yield and quality

Many reports detail changes in the incidence of common scab as a consequence of a change in liming policy or soil pH adjustment. In the report presented by Cogman (2018), the authors assessed the surface area affected with common scab in four categories, 0 %, 0-5 %, 5-20 % and >20 %, but presented their results only as the percentage of yield affected by scab. Conversations with four major packing companies during the period 2007-2013 (Stalham, personal communication; Stalham *et al*., 2015), indicated 5 % surface area was regarded as a rejectable limit for common scab. In seasons where tuber quality was poorer, the tolerances for common scab were relaxed, and vice versa in seasons where common scab incidence was low. In samples with a low frequency of tubers with high severity of scab, the severely-affected tubers could be graded out to lower-quality lines or stock feed, with the criterion being that the combined losses from all defects should not exceed 30 %. Where a high proportion of tubers in a sample fall close to the 5 % surface areas threshold for common scab, the entire load is likely to be rejected as a consequence of this disease, so when comparing improvements in overall packout, this threshold needs to be realized.

In order to examine the economics of liming policy and reductions in common scab, some simple economics need to be established. These relate to assessing the proportion of tubers in the packable versus rejectable categories being delivered to the packhouse, the value of the premium, scab-free product and the rejected tubers and the cost of the product(s) being applied (including application costs).

Cogman (2018) attempted a simple cost : benefit analysis using the results from their 12 trials with the susceptible variety Maris Piper. They used an average graded yield of 50 t/ha and an average price of £250/t for 1st Grade (scab-free) potatoes and £150/t for 2nd Grade potatoes. The cost of the LimeX delivered and spread at 7.5 t/ha was £112.50/ha. They found an increased yield of 1st Grade tubers of 5 t/ha and this should equate to £1250/ha, realizing a net benefit of £1138/ha. Their actual net gain was published at £388.

Using a more thorough approach of < 5 % surface area scabbed being acceptable for Grade 1 packing in Maris Piper, it is possible to estimate the yield benefit from several trials conducted at sites managed by Cambridge University Farm.

Using a value of £350/t for stored, April-delivery Grade 1 Maris Piper (AHDB) and £150/t for material deemed fit only for processing owing to moderate-severe scab, the net margin for liming in terms of improvement in scab can be calculated for a susceptible variety. With varieties with much higher resistance to scab (e.g. Electra, Jelly, Lanorma or even intermediate varieties such as King Edward), the economic benefits of lime application on scab would be marginal. Lime price varies according to type of dressing, grade of mineral (particle size and consistency), location and ease of spreading and could be as low as £2.50 per tonne ex-quarry to £26 ex-quarry (Redman, 2018). A short haul would cost about £5.50 and spreading *c*. £4.75 per tonne, adding £10 to the ex-quarry cost. Redman (2018) quotes lime prices averaging around £23.50 delivered and spread per tonne with an application rate of 6 t/ha per application, equating to £141/ha.

The lime trial of Hogge & Stalham in 1994 (Stalham, unpublished data) would show a benefit of liming of *c*. £440/ha in terms of improvement in scab and that of Allison (2000a) would show a benefit of £620/ha in terms of improvement in scab (Table **8**).

Over the trials and experiments listed above, a cost : benefit analysis using the scab-susceptible variety Maris Piper realized a net benefit of £440-£1138/ha resulting from an improvement in marketable yield from a reduction in scab. However, Maris Piper is the most scab-susceptible variety commonly grown in the UK, and for varieties with much high resistance to scab (Groups 3 and 4 in Stalham, 2015), these financial benefits would be reduced by at least a magnitude and possible be neutral in terms of cost : benefit. There were no experiments conducted on Group 2 (Susceptible) varieties, so no recommendations can be formed as to the likely benefit of lime on scab.

Table 8. Cost : benefit analysis of different rates of lime on scab in Maris Piper (Allison, 2000a). Values based on £250/t Grade 1 and £150/t Grade 2

Lime treatment (t/ha)	**Cost of product spread (£/ha)**	**Yield (t/ha)**	**Proportion of tubers <5 % surface area scabbed (%)**	**Value Grade 1 (£/ha)**	**Total value (£/ha)**	**Benefit compared with no lime (£/ha)**
0	0.00	37.1	89	8255	8867	0
3.5	82.25	39.2	92	9016	9486	620
7	164.50	32.8	97	7954	8102	-765
S.E. (6 D.F.)		1.37	2.2	301	297	32.5

Gypsum is a cheap product at £2-5/t (averaging £3/t), depending of time of year and stocks in agricultural suppliers. At the rates tested by Allison & Stalham (1999) and Allison (2000b), typically 0.5-5 t/ha, the same prices for haulage and spreading as for lime would apply (£10/ha). However, at rates >1 t/ha, a deployment charge for land remediation must be paid to the Environment Agency. This costs £2300 for up to 100 ha of close-proxity blocks of land. Details of the cost benefits of the trial conducted by Allison (2000b) are shown in Table **9**. In the two years of experimentation (Allison & Stalham 1999; Allison 2000b), gypsum improved the economic performance of the crops, and much more significantly than the addition of lime in their other experiments. In 1998, the effect was mainly in reducing the proportion of severely scabbed (>12.5 % SA) tubers, whilst in 1999, there was a reduction in both severely and moderately scabbed tubers. Allison (2000b) concluded that the exact mechanism of control of scab by gypsum remained unclear, but as mentioned earlier in this review, gypsum probably adds a soil conditioning function and increases easily available water holding capacity of the soil surrounding the tubers. However, as pointed out in the economic study on liming, growing varieties with much high resistance to scab than Maris Piper would reduce these financial benefits by at least one magnitude.

Table 9. Cost : benefit analysis of different rates of gypsum on scab in Maris Piper (Allison, 2000b). Values based on £250/t Grade 1 and £150/t Grade 2

Gypsum treatment (kg/ha)	Cost of product spread (£/ha)	Yield (t/ha)	Proportion of tubers <5 % surface area scabbed (%)	Value Grade 1 (£/ha)	Total value (£/ha)	Benefit compared with no gypsum (£/ha)
0	0.00	87.3	32	6984	15889	0
0.5	6.50	89.7	40	8970	17043	1154
1.0†	13.00	84.4	58	12238	17555	1609
5.0†	65.00	87.1	68	14807	18988	3042
S.E. (18 D.F.)		5.50	7.31	1505.0	2431.7	209.2

†Includes EA Deployment Fee of £57.50/ha for spreading gypsum on 40 ha

6.2. Tuber quality

Numerous studies have reported potential benefits for tuber yield and quality from applying calcium products. The detail of this is beyond the scope of this report, so is only covered briefly. The methods of application (timing and location) of these products is discussed where data are relevant and available.

6.2.1. Calcium and tuber number and size

In a pot study, Ozgen & Palta (2005) added calcium chloride and calcium nitrate as a liquid application to the soil at the equivalent rate of 168 kg Ca/ha. This increased the amount of calcium found in the periderm and results showed a reduction in tuber number compared to plots that only received nitrogen. Tuber sizes were larger following the application of calcium products than in non-split nitrogen applications (although not in split nitrogen). The mechanism for an effect of calcium on tuberisation is unknown, but it may relate to the role of gibberellic acid (GA) in signalling for tuberisation, and a modulation of this through a 'calcium/calmodulin pathway' (Vega *et al.*, 2006). Overall yield was not significantly different between treatments, supporting the theory that tubers were fewer, but larger in the calcium-treated plants. This has implications as certain markets (e.g. bakers) may require fewer larger tubers, whereas more, smaller tubers may be preferred for seed or salad potatoes. Similar results have been reported in other laboratory-based studies (Upadhyaya *et al*., 2016; Siefu, 2017; Gumede (thesis), 2017; Abbasian *et al*., 2018) and with microtubers (Arvin *et al*., 2005). In field experiments, Simmons & Kelling (1987), found no effect of calcium sulphate ($CaSO_4$) on total yield over four sites at a range of rates between 0 and 588 kg Ca/ha. Effects on tuber size varied between sites and years, with some improvements in percentage of tubers at premium grades (<107, 170-370 and >370 g) The application of 424 kg Ca/ha increased the top grades of tubers from 65.2 % to 74.2 %, and reduced the percentage of tubers below 170 g on low calcium soils (as determined by a soil test). The effect became less consistent as soil test calcium level increased, both between sites and over successive years (i.e. increases were not repeated in the second year of application).

Banerjee *et al.* (2014), also in field experiments, found that applications of gypsum gave a higher number of medium-sized (50-75 g) and large (>75 g) tubers at 120 kg/ha. Tawfik *et al*. (2001) found no effect of calcium application on tuber size distribution. Many more field-based studies would be needed to establish the extent and repeatability of an effect of calcium application on tuber number and size, and any interactions with other factors such as variety, other nutrients (particularly phosphorus), application rate and method.

6.2.2. **Calcium and skin quality**

Many industry sources cite the use of calcium products, including gypsum, to improve skin finish. For example, a study by WRAP and Velcourt (WRAP, 2007) found slight improvements in skin finish between plots treated with agricultural and recycled gypsum and untreated plots, which was attributed to calcium. In a report commissioned by BPC, Wiltshire *et al*. (2006) found no effect of calcium on skin set and no differences between treatments were found. Limited academic papers since 2004 were found on this subject, however calcium is known to play a key role in thickening and strengthening of tuber periderm (particularly in wound healing) (Lulai, 2007). Ginzberg *et al.* (2012) explored the 'Magen russeting' of smooth skinned potato variety tubers in Israel, which is caused when old phellem skin cells adhere to new cells formed below them, leaving patches of rough skin. Russeted skin areas have higher concentrations of calcium and lower concentrations of potassium than smooth skin areas, independent of calcium or potassium fertilisation and irrigation (Ginzberg *et al.*, 2012). The primary cause of this russeting (and whether the accumulation of calcium was causal – perhaps reducing sloughing off of skin cells leading to russeting – or a symptom) was not determined, but in tubers where calcium was applied, russeting incidence was reduced.

6.2.3. **Calcium and internal defects and disease**

A large number of studies have found reduced incidence of internal defects and disease including soft rot (*Pectobacterium carotovorum*, *Pectobacterium atrosepticum*, *Dickeya* spp. previously genus *Erwinia)*, bruising damage and internal brown spots, following the application of calcium.

The review by Palta (2010) covers a wide range of tuber quality traits that have been improved through application of calcium. Increased calcium concentration in the peel and medullary tissue of tubers has been found to be best achieved through application to the upper portion of the ridge where tubers are developing via irrigation during tuber bulking (Palta, 2010).

6.2.3.1 Soft rot

Reduced incidence of soft rot from calcium fertilisation has been found in many studies, and is hypothesised to be due to the role of calcium in cell membrane and wall strength, which counteracts the effect of the bacteria (McGuire & Kelman, 1984; Palta, 2010; Czajkowski *et al*., 2011; Mantsebo *et al.*, 2014; Tuhwe (thesis), 2015). The role of both calcium and pectin in the physiology of resistance to soft rot in less susceptible cultivars via cell wall strength was highlighted in Abo-Elyousr *et al*. (2010a; 2010b; 2016). Ngadze *et al*. (2014; 2018) found that soil amendments of calcium increased calcium concentration in tuber peel and that there was a significant positive correlation between calcium levels and metabolism of the phenolic compounds caffeic and chlorogenic acids and plant defensive enzymes phenylalanine, polyphenol oxidase and peroxidase. The mechanism of damage by soft rot is pectolytic enzymes which induce polyphenol oxidase activity which macerate plant tissues. Ngadze *et al*. argue that reduced incidence of maceration damage (in both extent and size of wounds) caused by *Pectobacteria* species was due to the anti-microbial properties of these acids.

6.2.3.2 Internal brown spot

Ozgen *et al*. (2006), found split applications of calcium (calcium nitrate and calcium chloride) at 100-200 kg/ha reduced internal brown spot defects in Russet Burbank, from 20 to 5 %. As multiple factors contribute towards internal defects, there was still great variation in incidence at each level of tuber calcium concentration. This study also added gypsum as an additional treatment but found no effect on tuber calcium concentration or internal brown spot. Previous studies have also found a link between internal calcium concentration and reduced internal brown spot (Tzeng *et al*., 1986; Olsen *et al*., 1996; Kleinhenz *et al*., 1999).

6.2.3.3 Bruising

Karlsson *et al*. (2006) found an inverse correlation between blackspot bruising caused by mechanical injury and tuber calcium concentration, where high tuber calcium concentration cultivars had lower bruising than low calcium concentration cultivars. The mechanism for this again is posited to be cell wall strength increases inferred by higher calcium concentration (calcium chloride and calcium nitrate were added in three splits at a rate of 168 kg/ha during bulking and led to increased calcium levels of up to 30 %).

6.2.4. **Other calcium effects**

6.2.4.1 Improved reaction to environmental stress (heat and cold)

Heat stress in potato can result in reduced carbon fixation and partitioning to tubers, declines in plant and tuber growth and impaired TI and tuber development (Kleinhenz & Palta, 2002). In field trials in Egypt, Tawfik *et al*. (1996) found significantly greater leaf membrane stability and tuber fresh weight in plants that received a calcium and nitrogen treatment in the tuber zone area, compared to those that only received nitrogen. The suggested mechanism for this is the role of calcium in maintaining stomatal conductance during heat stress, and may help apical meristem damage and cell expansion (LAI in plants under heat stress tends to be reduced). The benefits of higher levels of calcium supplementation (greater than 125 µM) to roots in terms of increased foliar fresh weight and leaf area in potato plants under heat stress were replicated in a more precisely controlled follow-on laboratory study (Kleinhenz & Palta, 2002). This study reported that potato plant growth persisted at specific levels of root zone calcium (greater than 125 µM, and that the calcium required for growth under heat stress exceeded that required for growth under normal temperatures. The mechanism for protection again heat stress was not fully elucidated but the authors suggest that improved cell expansion in calcium treated plants compared to untreated plants may play a key role. The impact of the treatments on tubers was not covered.

Ina laboratory study, using a system of pure silica sand, Vega *et al*. 1996 found that soluble calcium supplementation reduced frost damage, possibly due to its role in helping to repair damage to cell walls caused by frost. Palta (2010) found varietal differences in the ability to accumulate calcium, demonstrated by variable performance in the same environmental conditions. This may be a heritable tuber quality trait that could be improved through breeding.

6.2.4.2 Fry quality

The effect of tuber calcium on fry quality was discussed in a study by Agblor & Scanlon (2002). The aim of the study was to reduce variations in colour and texture in French fries. Russet Burbank and Shepody varieties grown at two sites (Carberry and Portage) were stored for 9 and 11 months. Fries processed from Portage had better texture but darker colour than those grown at Carberry. These results were attributed to differences in tuber calcium content associated with higher soil calcium levels at Portage. The study concluded that increased tuber calcium increase the extent of formation of calcium-pectate complexes during processing which could affect strengthening (and hence texture) preventing the leaching of soluble substances during blanching (and therefore fry colour).

7. Potential areas for future research

This review has uncovered several areas where knowledge is lacking on the effects of pH and calcium on crop performance and quality. The potential areas for future research include:

- Using the British Geological Survey United Kingdom Soil Observatory Soil map viewer (http://mapapps2.bgs.ac.uk/ukso/home.html) to show the distribution of soil pH in potato-growing areas and correlate with actual potato crops to corroborate British Survey of Fertiliser Practice survey data.
- Whether the current recommendations for liming ahead of potatoes are correct when pH is not increased above 7.5 as a result of liming and only need to be modified for high pH soils where brassicas or sugar beet are grown.
- Confirmation of the upper and lower limits of pH tolerance for the pathogenic species isolated in the UK, including *S. europaeiscabiei*.
- A survey of pathogenic scab species found in the UK. Dees & Wanner (2012) stated "On the pathogen side, lack of understanding of the types and consequences of genetic diversity and the genetic basis for differences in aggressiveness of isolates hinders development of control strategies".
- More research is needed on the mechanisms of resistance/susceptibility to common scab. Information on pathogen variability is also essential in selecting common scab-resistant plant germplasm. On the plant side, the physiological or genetic basis for differences in scab severity seen in different potato cultivars is poorly understood, and no source of true resistance to common scab has been identified (Powelson *et al.*, 1993; Hosaka *et al*., 2000; Agrios 2005). Physiological differences such as skin set properties and thaxtomin sensitivity may partly explain differential cultivar susceptibility, but knowledge is limited.
- Effect of calcium application on fry quality in both French fries and crisps.

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